Development of high-performance and durable engineered wood products from mountain pine beetle veneers using novel resin impregnation technologies

Brad Jianhe Wang, Y. H. Chui*, Guangbo He, Dan Xie*

Mountain Pine Beetle Working Paper 2009-10

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Abstract

This project investigated the technical feasibility and economic benefits of using phenol formaldehyde resins to treat mountain pine beetle-attacked lodgepole pine (*Pinus contorta* Dougl.) veneers and to produce high-performance, durable engineered wood products. These products have the potential to significantly increase the value recovered from mountain pine beetle wood. A breakthrough resin impregnation technology was developed and a special phenol formaldehyde resin was formulated which significantly simplified the manufacturing process of veneer-based engineered wood products, making it much more cost-effective. The resulting products improved appearance, surface hardness, stiffness, strength, dimensional stability, and decay resistance. They were also environmentally friendly. Because of these features, they can be extensively used for value-added structural and industrial applications and will be able to compete successfully with wood plastic composites and other materials in exterior applications. The new resin impregnation technology is equally applicable to other common Canadian species, such as spruce and aspen. At the current resin price, the application of this technology will result in significant economic gains for Canadian plywood/laminated veneer lumber producers.

Keywords: Drying, impregnation, laminated veneer lumber (LVL), lodgepole pine, moisture content (MC), mountain pine beetle (MPB), phenol formaldehyde (PF), plywood, resin solids uptake, stain, veneer

Résumé

Dans le cadre du projet, on a étudié la viabilité technique et les avantages économiques de l'utilisation de résines de phénol-formaldéhyde (PF) pour traiter le bois de placage des pins tordus latifoliés (*Pinus contorta* Dougl.) attaqués par le dendroctone du pin ponderosa (DPP) et fabriquer des produits de bois durables de haute performance et de haute technologie. Ces produits pourraient augmenter de manière considérable la valeur de récupération du bois attaqué par le DPP. Une technologie innovante d'imprégnation de résine a été élaborée et une résine spéciale de PF a été mise au point, qui a grandement simplifié le processus de fabrication des produits de bois durables de haute performance et de haute technologie à base de bois de placage, tout en le rendant beaucoup plus rentable. Les produits ainsi obtenus montraient de nettes améliorations quant à l'apparence, la dureté superficielle, la rigidité et la résistance, la stabilité dimensionnelle et la résistance à la pourriture. Ils étaient également plus écologiques. Grâce à ces propriétés, ils pourront être utilisés à grande échelle pour les applications structurelles et industrielles à valeur ajoutée et pourront faire concurrence aux composites bois-plastique (CBP) et à d'autres matériaux dans les applications extérieures. La nouvelle technologie d'imprégnation de résine peut également être appliquée à d'autres espèces canadiennes courantes, telles que l'épinette et le tremble. Au prix actuel de la résine, l'utilisation de cette technologie permet aux fabricants canadiens de contreplaqués et de LVL de réaliser des gains économiques importants.

Mots clés: séchage, imprégnation, bois en placage stratifié (LVL), pins tordus latifoliés, taux d'humidité (TH), dendroctone du pin ponderosa (DPP), phénol-formaldéhyde (PF), contreplaqué, absorption de la résine, tache, bois de placage

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1 Introduction

Over the past several years, the mountain pine beetle (*Dendroctonus ponderosae*, MPB) infestation in British Columbia has substantially damaged a vast amount of lodgepole pine (*Pinus contorta* Dougl.). By 2015, an estimated 76% of the merchantable lodgepole pine will have died. The sheer magnitude of this epidemic has created many challenges for the wood industry (Forestry Innovation Investment 2008 a, b). For example, MPB wood has a lower moisture content (MC), and has checks and various levels of blue stain that result in lower material recovery, more labour intensity, and cosmetic concerns. British Columbia has a large wood veneer products industry, producing predominantly plywood and laminated-veneer lumber (LVL). Post-MPB veneers are generally used for making sheathing-grade plywood (CSA 2004, 2007). Compared with control spruce-lodgepole pine-subalpine fir (SPF) plywood, MPB plywood has better gluebond quality and bending performance but its stained surface and reduced material recovery (Wang and Dai 2004; Wang et al. 2005; Wang 2007; Wang et al. 2008) have made British Columbia plywood mills lose market share and mill profit. Mills are now reluctant to process MPB wood unless new product options can be found that increase their profit margin.

Wood products are widely accepted and extensively used in the residential housing market in North America. Still, concerns about their dimensional instability and susceptibility to biological attack limit their market access in extended industrial/structural and exterior applications (Eaton and Hale 1993; AWPA 1997; CSA 1997; APA 1999; FCC and CWC 2004; Forest Products Laboratory 2004; Wan and Kim 2006; Kamke and Lee 2007; Mourant et al. 2007; Przewloka et al. 2007). Chemical treatments are often used to improve their durability (Yasuda et al. 1994), but they can also reduce wood strength and harm aquatic environments. This is because preservatives such as alkaline copper quaternary (ACQ) are not crosslinked at the molecular level with wood, and copper in treated wood is readily leached in the field (Mourant et al. 2007).

By comparison, resin impregnation of wood could offer a robust solution to improve product appearance and performance, such as hardness, stiffness and strength, and dimensional stability (Hare and Kutscha 1974; Nearn 1974; Nicholas and Williams 1987; Brady and Kamke 1988; Troughton and Steiner 1992; Walser et al. 1993; Chui et al. 1994; Troughton and Steiner 1994; Miroy et al. 1995; Gindl et al. 2003; Shams et al. 2004; Zhang et al. 2006; Kamke and Lee 2007). It should also increase product durability (Militz 1993; Yusuf et al. 1994; DIN 2002; Wepner and Militz 2005; Wan and Kim 2006; Wepner et al. 2006; Kamke and Lee 2007). Mourant et al. (2007) demonstrated that the phenol formaldehyde (PF) pyrolytic oil resin treated wood has improved decay resistance, and PF glue can inhibit the growth of fungi in plywood modified by DMDHEU (1.3-dimethylol-4.5-dihydroxy ethylene urea) (Dieste et al. 2008). Products that retain a threshold level of resin solids could meet the standard requirements of maximum allowable mass loss and be decay resistant (Kajita and Imamura 1991; Ryu et al. 1991; Lewis 1995; Van Acker et al. 1999, 2001). However, the current resin impregnation process is simply not cost-effective. Retaining more resin may require investing in vacuum-pressure equipment (Wan and Kim 2006). Also, using resin impregnation technologies to manufacture LVL and plywood generally requires dual-resin applications: one for impregnation/penetration, the other for interfacial bonding of veneer to veneer after drying (Troughton and Steiner 1992, 1994; Chui et al. 1994; Gindl et al. 2003; Wan and Kim 2006; Kamke et al. 2007; Dieste et al. 2008). As a result, given the relatively higher price of the resin, none of the plywood/LVL mills in North America are adopting resin impregnation technologies to manufacture high performance and durable engineered wood products (EWPs).

Despite unfavourable cosmetic and recovery issues, MPB-attacked lodgepole pine, especially stained wood (sapwood), has a high permeability, which could significantly ease resin impregnation (Wang et al. 2005; Wang et al. 2008). This high permeability means a simple resin treatment method, such as dipping/soaking, could be used without involving vacuum-pressure to cost-effectively manufacture high-performance and durable EWPs from post-MPB veneers. As well, the manufacturing process could be

simplified by eliminating further resin applications after veneer drying. In terms of cosmetic appearance, melamine formaldehyde (MF) resins are colourless and may not modify the colour of wood effectively, but brownish PF resins could effectively mask the blue stain in post-MPB veneers.

No information is available concerning resin impregnation of MPB veneers and the resulting product performance. With PF-resin impregnation, it is anticipated that: 1) blue stain in MPB wood can be easily masked; 2) product dimensional stability, hardness and bending performance can be significantly improved; and 3) product durability such as decay resistance can be substantially enhanced. These improvements, if cost-effective, will provide potential for extended industrial/structural and exterior applications such as concrete forms, container floors, decking and flooring, siding and fencing, balcony and landscaping items, and so on.

This project comprised four major research components.

First, a fundamental understanding of resin impregnation was developed using a low molecular weight (MW) commercial PF resin to treat dry and green MPB veneers. The resin solids uptake between stained and unstained MPB veneers was also compared. The drying characteristics of treated veneers were further investigated.

Second, a special PF resin was developed to mask the stain colour in MPB veneers and eliminate the need for further resin applications in manufacturing value-added plywood. Cost-effective treatment/drying recipes were also established in terms of dipping/soaking time, drying temperature and time.

Third, using the new PF resin, the relationship between veneer modulus of elasticity (MOE) and resin-solids uptake was established, and the overall performance of MPB LVL was characterized in terms of resin-solids uptake. Furthermore, the formaldehyde content of MPB products was determined through a perforator test (European Standard 1988; British Standard 1992), and the decay resistance of MPB products was evaluated in terms of resin-solids uptake with a laboratory soil-block test (AWPA 2008).

Finally, the feasibility of resin impregnation of post-MPB veneers for making high performance and durable EWPs was determined and its economic benefit assessed.

2 Materials and Methods

Four hundred full-size (1.2 x 2.4 m) dried MPB and 50 full-size green MPB veneer sheets were obtained from an interior British Columbia plywood mill for resin-impregnation tests and plywood/LVL manufacturing. Fifty veneer sheets (1.2 x 2.4 m) of each of dried non-beetle attacked lodgepole pine, white spruce, and trembling aspen were also obtained for comparison tests.

2.1 Pilot plant tests of MPB veneers impregnated with low molecular weight PF resin

Sixty full-size dried and 30 full-size green MPB veneer sheets were randomly selected and sorted into stained (sapwood) or unstained (heartwood) categories. For dried MPB veneers, sixty 40.6 x 40.6 cm and sixty 10.2 x 10.2 cm specimens each were randomly cut from each category. The average MC for oven-dried veneer was 6%. In addition, eighty 10.2 x 10.2 cm specimens were randomly cut from the other 40 unsorted full-size MPB veneer sheets. For green MPB veneers, twenty 10.2 x 10.2 cm specimens were randomly cut from each category.

A commercial low-MW PF resin for oriented strand board (OSB) face layers was acquired from a resin supplier and diluted for resin impregnation. Dried and green MPB veneer specimens, stained and unstained, were impregnated with this resin at different dipping/soaking times then air- or oven-dried. The resin solids uptake curve was developed based on soaking time. Comparisons were made between dried

and green MPB veneers, and between stained and un-stained MPB veneers in terms of resin solids uptake, drying characteristics, and final veneer MC. In addition, 5-ply plywood panels were made from treated stained and unstained MPB veneers. Their colour, surface hardness, gluebond quality, parallel-ply bending performance and dimensional stability were evaluated and benchmarked against those of commercial plywood made from untreated veneers (Awoyemi and Jarvis 2007; CSA 2004; ASTM 2006; CSA 2007; Goktas et al. 2008).

2.1.1 Effect of dipping time on resin-solids uptake of dry MPB veneers

Ten 10.2 x 10.2 cm specimens were randomly selected from the stained and 10 from unstained dried MPB veneer. Before dipping/soaking in the diluted low MW PF resin, the five-point thickness, length, width and weight were measured for each specimen. The oven-dried weight (0% MC) of each specimen was derived. After dipping for 1, 2, 5, 10, 20, 60, 120, 240, 1260, and 1440 min, the weight of each specimen was measured to calculate the resin solids uptake.

2.1.2 Effect of dipping time on resin-solids uptake of green MPB veneers

To determine the feasibility of resin impregnation for green MPB veneers, the same diluted low MW PF resin was used. Ten 10.2 x 10.2 cm specimens were randomly selected from the stained and 10 from unstained green MPB veneer. Before dipping/soaking in the resin, the weight of each specimen was measured to estimate its initial MC. After dipping for 1, 2, 10, 60, 180, 360, 1380, and 1680 min, the weight of each specimen was measured to calculate the resin-solids uptake.

2.1.3 Drying of resin impregnated MPB veneers

To determine the drying characteristics of veneers impregnated with the diluted low MW PF resin, twenty 10.2 x 10.2 cm dried stained and 20 unstained MPB veneer specimens were further selected. Ten specimens from each category were dipped in the resin for 1 min and the other 10 for 5 min. Then all were weighed. Among the 10 specimens, five specimens were selected for air-drying and the remaining five specimens for oven-drying.

To determine the optimum drying time for the resin-impregnated MPB veneers, twelve 10.2 x 10.2 cm dried MPB veneer specimens were randomly selected. No efforts were made to differentiate the stained and unstained veneers since the commercial MPB veneers could contain both stained and unstained portions. Specimens were dipped in resin for 5 min and weighed. Then half of the specimens were selected for air-drying and the other half for oven-drying.

2.1.4 Manufacturing and testing 5-ply plywood from resin-impregnated MPB veneers

Twenty 40.6 x 40.6 cm dried stained and 20 unstained MPB veneer specimens were randomly selected and dipped in the diluted resin for 5 min and dried until reaching 3%–6% MC, and passed through a roller spreader to achieve a target glue spread level of 32 lb/1000 ft^2 per glueline with a commercial plywood PF glue mix. Three 5-ply plywood panels (40.6 x 40.6 cm) were manufactured from each category. The pressing temperature and pressure were 155°C and 175 psi, respectively. After unloading, the panels were stacked for 48 h before cutting for testing plywood colour change, hardness, gluebond quality, bending performance, and dimensional stability.

To benchmark the colour change after the resin treatment, six 19 x 19 mm cubes were randomly cut from each of five typical stained and unstained MPB lumber blocks. In addition, 30 cubes (19 x 19 mm) were cut from five MPB plywood panels manufactured from the same Interior British Columbia plywood mill. Thirty 19 x 19 mm cubes were also cut from stained and unstained wood for the 40.6 x 40.6 cm 5-ply MPB plywood panels.

Colour measurements were conducted according to the ISO 7724 Standard (1984). A spectrophotometer (Konica Minolta model CM-600d) was used to measure the colour index L*, a* and b* of the cubes (Goktas et al. 2008). The L* axis represents the lightness and varies from 100 (white) to zero (black); the a* and b* coordinates represent chromaticity, with + a* for red and – a* for green, and + b* for yellow and – b* for blue. The comparison was made in colour difference among the stained MPB wood, unstained MPB wood, mill MPB plywood, stained MPB plywood and unstained MPB plywood. Furthermore, using the stained and unstained MPB wood as controls, the colour differences (ΔE*) of the stained and unstained MPB plywood panels were determined according to the following equations:

$$\Delta L^* = L^*_p - L^*_w \quad (1)$$

$$\Delta a^* = a^*_p - a^*_w \quad (2)$$

$$\Delta b^* = b^*_p - b^*_w \quad (3)$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (4)$$

ΔL*, Δa*, and Δb* are the changes between plywood (p) and wood (w) in terms of mean values of L*, a* and b*, respectively. These calculated changes from Equations 1–3 contribute to the overall colour change ΔE* as determined in Equation (4). Higher ΔE* values represent greater discolouration.

2.2 Developing a special PF resin formulation for veneer impregnation

To mask the stain colour in MPB veneers and simplify the manufacture of veneer-based EWPs using resin-impregnation technologies, a new PF resin formulation was developed in the pilot plant with a wide range of MW. Dipping veneers in this resin achieves suitable cell-wall penetration while retaining enough on the surface for interfacial veneer-to-veneer bonding without needing more glue after drying.

2.2.1 Manufacturing value-added plywood products from MPB veneers impregnated with a new PF resin

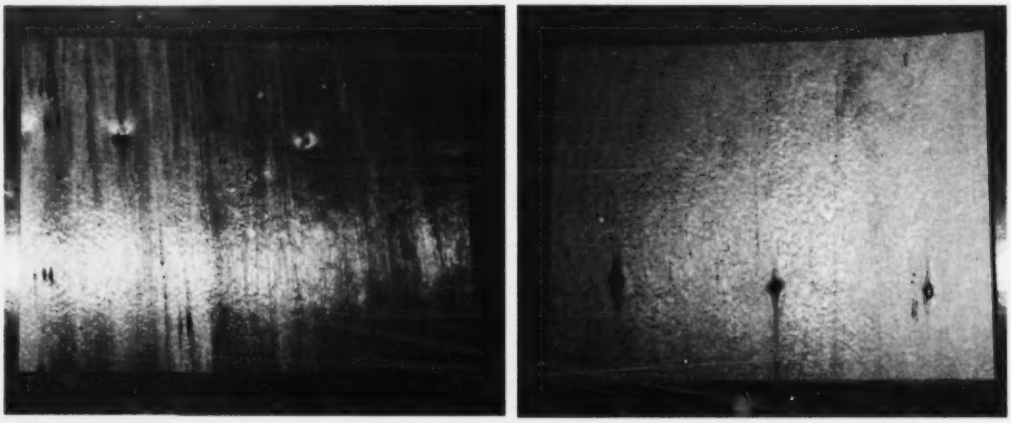
One hundred and fifty dried full-size (1.2 x 2.4 m) MPB veneer sheets were selected and classified as either mixed, stained (sapwood), or unstained (heartwood). For benchmark and comparison purposes, the 50 control sheets (1.2 x 2.4 m) from dried nonbeetle-attacked lodgepole pine, white spruce, and trembling aspen were also used. From these full-size sheets, 100 representative veneer specimens (10.2 x 10.2 cm) and 50 veneer sub-sheets (40.6 x 40.6 cm) were cut from the six types. Average veneer MC was approximately 6%, regardless of species and category.

2.2.2 Dipping tests of various veneer sheets

To examine the technical feasibility of using the special PF resin for impregnation, ten 10.2 x 10.2 cm veneer specimens were selected from the stained MPB, unstained MPB, control lodgepole pine, white spruce and aspen veneer. The dipping/soaking tests were performed to establish a relationship between resin-solids uptake and dipping time. Dipped veneers were weighed to determine the resin-solids uptake, and then dipped in the resin again at the next designated time, and so on, until the final 1440 min (24 h) was achieved.

2.2.3 Manufacturing and testing 5-ply plywood from resin-impregnated veneers

Fifteen veneer sheets 40.6 x 40.6 cm were selected from each of the stained MPB (Figure 1a), unstained MPB (Figure 1b), mixed MPB, control lodgepole pine, white spruce, and aspen. All veneer sheets were dipped in the new PF resin for 5 min and then weighed to calculate the resin-solids uptake (Figure 2). After oven-drying, the weight of each sheet was recorded to calculate its final veneer MC. The target final veneer MC was 8%–10%. Three 5-ply plywood panels were made from each species/category without further glue applications. Stained MPB, unstained MPB, mixed MPB and control lodgepole pine plywood were pressed at 200 psi; spruce and aspen plywood were pressed at 180 psi. Pressing lasted until the innermost glueline temperature reached 110°C. After unloading, the plywood panels were hot-stacked for 48 h before cutting specimens for colour change, hardness, gluebond quality, parallel-ply bending performance, and dimensional stability tests.



a) Stained b) Unstained

Figure 1. Stained and unstained MPB veneers.

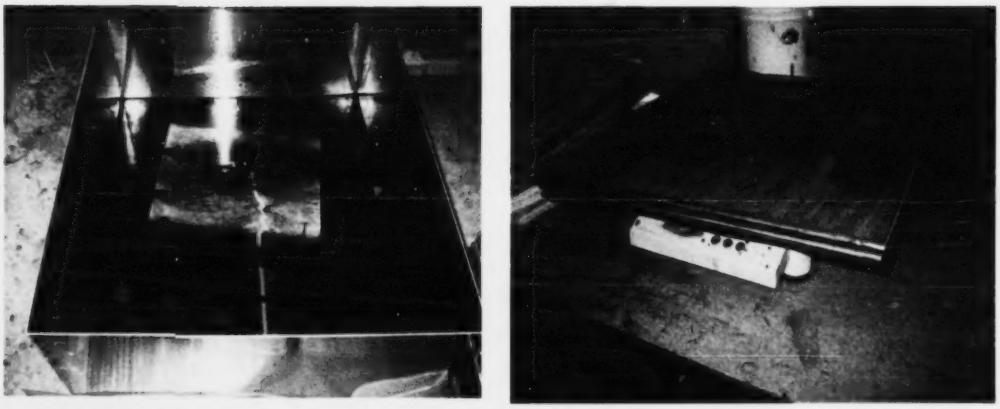


Figure 2. Resin-impregnation tests of MPB veneers.

Plywood gluebond quality was tested in terms of shear strength and percentage wood failure according to the CSA O151 standard (CSA 2004). Colour change was measured by the spectrophotometer to obtain the colour index L*, a* and b*. Parallel-ply bending performance was measured following the CSA O325

standard (CSA 2007). Plywood dimensional stability was examined in terms of 48-h water absorption and thickness swell. Hardness tests followed the ASTM D1037 standard (ASTM 2006). Figure 3 diagrams the sampling scheme for the various tests.

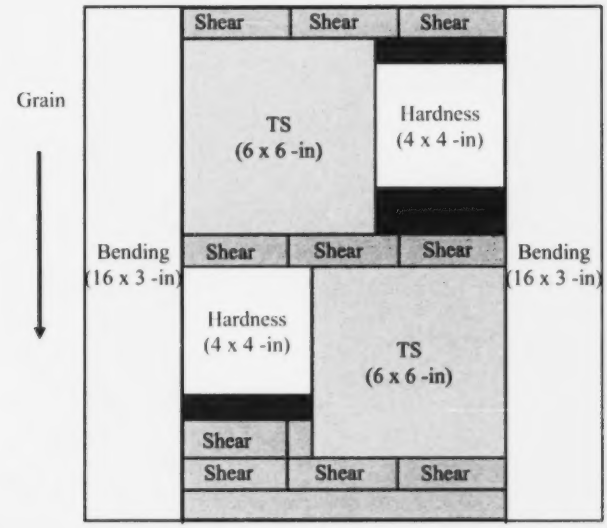


Figure 3. Plywood specimen cutting pattern for various tests.

Note: Blocks were reserved for durability tests (D): 16 each panel (19 x 19 mm or 0.75 x 0.75 inch); Shear samples: 10 each panel (81 x 25 mm or 3.3 x 1.0 inch); and the thickness swell (TS) samples were also used for colour measurements.

2.3 Manufacturing LVL from MPB Veneers Impregnated with a New Phenol Formaldehyde Resin

Sixty representative full-size (1.2 x 2.4 m) dried MPB veneer sheets were selected and used for this study. They were cut into 180 40.6 x 30.5 cm sub-sheets and classified into stained (95 sheets) and unstained (85 sheets) categories. Ten readings of stress wave time were measured from each sheet at a span of 30.5 cm from 10 lines, 2.5 cm apart, along the grain before the treatment (Metriguard Inc. 1998). Measured also were 9-point veneer thickness and weight of each sheet. From these measurements, the average density and stress wave time of each sheet can be determined and used to compute veneer dynamic MOE.

Vacuum-pressure treatment can increase resin retention faster than dipping/soaking. The new PF resin (30% solids content) was again used. To manufacture LVL with different levels of resin loading, the following five treatment recipes were used: soaking for 5 min, vacuum-pressure for 5 min, vacuum-pressure for 10 min, soaking for 1 h and soaking for 6 h (see Table 1 for experimental design). After treatment, veneer sheets were oven-dried to achieve 7%–8% MC, and the stress wave time, thickness, and density of each sheet were re-measured. Five-ply LVL billets were then manufactured with a laboratory mini-press (40.6 x 40.6 cm) using a thickness control method. Three replicates were used. After unloading, specimens were cut from LVL billets following the cutting pattern shown in Figure 4 (CSA 2004; CSA 2007; APA 2000; ASTM 2006; Goktas et al. 2008) and tested for hardness and colour change, as well as bending, shear, and thickness-swell tests. Shear tests followed the JAS Standard through a short span bending test (JAS 1993).

Table 1. An experimental design for resin-impregnation tests.

Test no.	MPB veneer category	Resin treatment	Time (min)
1	Stained	Soaking	5 min
2	Stained	Vacuum pressure	5 min
3	Stained	Vacuum pressure	10 min
4	Unstained	Soaking	5 min
5	Unstained	Vacuum pressure	5 min
6	Unstained	Vacuum pressure	10 min
7	Stained	Soaking	60 min
8	Stained	Soaking	360 min
9	Unstained	Soaking	60 min
10	Unstained	Soaking	360 min

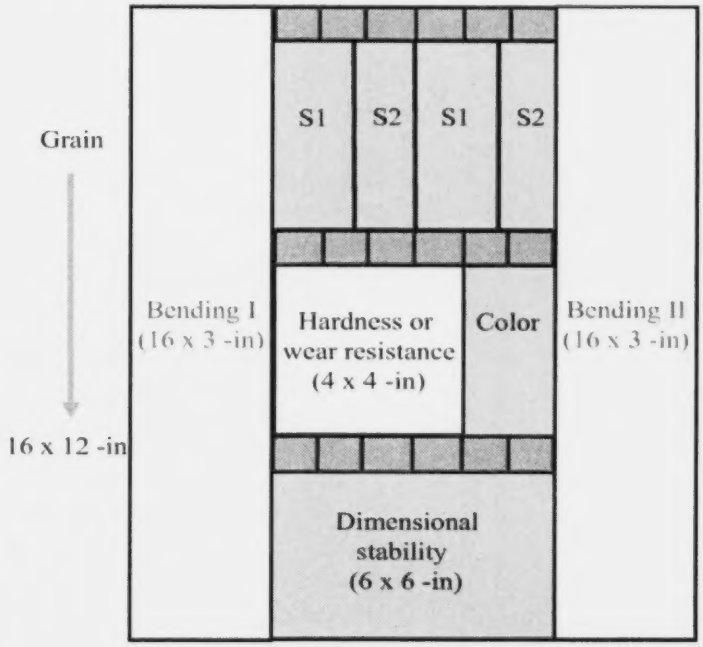


Figure 4. Laminated veneer lumber specimen cutting pattern.

Note: S1 is the shear test sample (L-X) in 95.3 x 40.0 x 15.5 mm and S2 is the shear test sample (L-Y) in 95.3 x 15.5 x 15.5 mm. The blocks (cubes) (19 x 19 mm) were reserved for durability tests.

2.4 Durability of plywood/LVL made from PF resin-impregnated MPB veneers

2.4.1 Perforator test

An evaporative ageing procedure may be required to evaluate loss in effectiveness when test blocks are subjected to biological attack. But this procedure requires 12 weeks for the exposure period (European

Standard 1988), and leaching the unfixed chemicals may make the material more susceptible to fungi attack (Dieste et al. 2008). As a compromise, a perforator test was first conducted to evaluate the free formaldehyde content at higher resin retentions. This test is based on the extraction of formaldehyde from the test tubes by using boiling toluene, which is then transferred to demineralized water. The formaldehyde contained in the water solution is photometrically established using an acetyl-acetone method. If the test shows no significant difference in the formaldehyde level in terms of different levels of resin-solids uptake, the ageing and/or leaching procedures could be unnecessary (British Standard 1992).

For the perforator test, three 5-ply LVL billets were selected with a resin-solids uptake of 12%, 25% and 38%. Two 15.2 x 15.2 cm samples were cut from each LVL billet (case). Ten 15.2 x 15.2 cm untreated MPB 3.2 mm veneer samples and two 15.2 x 15.2 cm 5-ply commercial plywood samples were also cut and used as the two control cases. For each of the five cases, at least 300 g material was guaranteed. These samples were wrapped in plastic bags and then shipped to FPInnovations–Forintek Eastern Division for the test.

2.4.2 Soil-block test

Preliminary screening of wood preservatives involves accelerated leaching of small blocks containing different concentrations of preservative, followed by a laboratory decay test to determine the minimum concentration of the preservative that will prevent decay. The threshold value generated may then be used as a meaningful reference point for further evaluation. The rate of decay depends on the properties of the wood under test, the test fungi used and the environmental conditions of the test (Przewloka et al. 2007). Lodgepole pine sapwood (stained or not) and heartwood easily decayed in a laboratory soil-block test and showed little natural durability.

Blocks (19 x 19 mm) cut from plywood and LVL panels made from PF resin impregnated MPB veneers were used for the laboratory soil block tests (Figures 3 and 4). Twenty blocks were prepared for each test condition. The test method followed was generally as described in the AWPA E10-08 Standard for laboratory soil block testing (AWPA 2008).

Blocks were conditioned at 40°C in a forced-draught oven and weighed. Cylindrical glass jars (500 mL) were half-filled with soil (horticultural loam) that was adjusted to approximately 50% MC. The soil was topped with two 35 x 29 x 3-mm ponderosa pine sapwood feeder strips, the jar was closed, and the assembly sterilized by autoclaving at 103.4 kPa and 121°C for 1 h. After cooling on a clean air bench, each jar was inoculated with one of the following wood-rotting basidiomycetes grown on 1.5% malt, 2.0% agar (Difco):

Coniophora puteana (Schum. *ex* Fr.) Karst.	Ftk 9 G
Irpex lacteus (Fr.) Fr.	Ftk 103 A

Coniophora puteana (C. puteana) is a common brown-rot fungus while *Irpex lacteus (I. lacteus*) is a common white-rot fungus. Both are specified in the AWPA E10-08 standard test although this specific strain of *C. puteana* is not listed. Following inoculation, jars were closed with a sterile lid containing a vent hole sealed with a membrane filter to exclude contaminants. White rot-inoculated jars were incubated for 4.5 weeks at 25°C and 80% relative humidity while brown rot-inoculated jars were incubated for 3.5 weeks before the irradiated blocks were aseptically placed, two per jar, on top of the feeder strips.

Jar assemblies were then incubated for a further 12 weeks (brown rots) or 24 weeks (white rots). The latter test is still under way at the time of reporting. After incubation, blocks were removed from jars, cleaned of adhering mycelium, weighed, conditioned at 40°C in a forced-draught oven, and re-weighed. Block MCs and weight losses were then computed based on the post-leaching conditioned weight and the conditioned weight following removal from the soil jar. Weight losses were corrected using non-inoculated treated check block results to compensate for any non-fungal weight loss or gains. Decay was

confirmed by a visual inspection of the test blocks. The relationship between the weight loss due to decay and resin-solids uptake was established for brown rot fungus. The threshold retention is determined by visual inspection and by estimating the point at which weight loss caused by decay does not occur (AWPA 2008).

There were minor variations from the Standard method. In leaching the samples, more than four blocks were placed in an appropriately-sized container, but the ratio of blocks to water volume in the Standard was followed. A full cell treatment process was used in this study to ensure complete penetration of samples. The Standard requires water impregnation using a water-pump aspirator; however, this sometimes results in poor and uneven uptakes.

The soil was adjusted to approximately 50% MC. The Standard requires that the soil be added to the jars and topped with a measured amount of water to 130% of the water-holding capacity of the soil; however, this frequently results in waterlogged conditions and poor growth of basidiomycetes.

3 Results and Discussion

Results are summarized in four components.

3.1 Pilot plant resin impregnation and plywood manufacturing tests with a low MW PF resin

3.1.1 Relationship between resin-solids uptake and dipping time for dry MPB veneers

Stained MPB veneers showed much faster and higher resin solids uptake than unstained veneers (Figure 5). After 24 h dipping/soaking, the average resin solids uptake was about 18.5% for the stained veneers as compared to 13.0% for the unstained veneers. This difference was largely attributed to the higher permeability of stained (sapwood) MPB veneers.

Both stained and unstained MPB veneers showed the fastest resin uptake within the first 10 min during 1 h dipping (Figure 6). With merely 5 min treatment, the average resin-solids uptake was 10.0% for the stained veneers as compared to 7.1% for the unstained veneers. Soaking veneers for 5 min may be an economical step in improving the cost-effectiveness of resin impregnation.

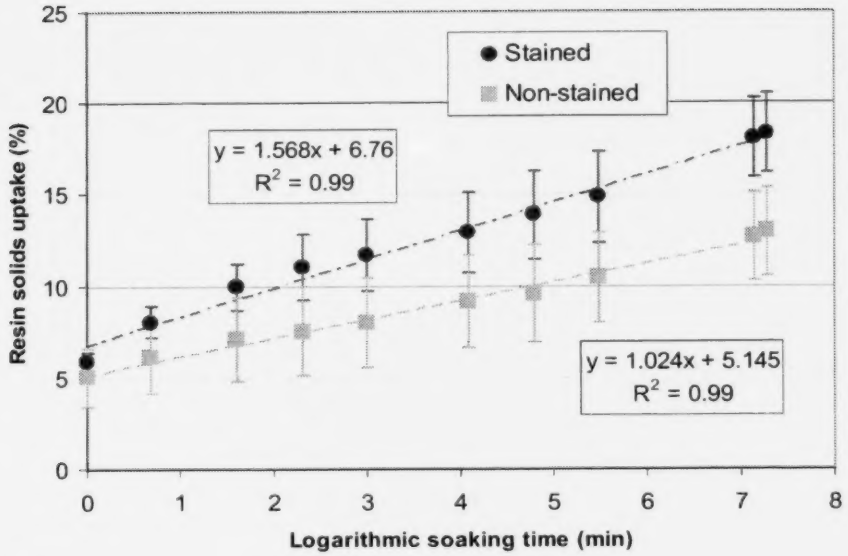


Figure 5. Change of resin-solids uptake with soaking time for dry MPB veneers.

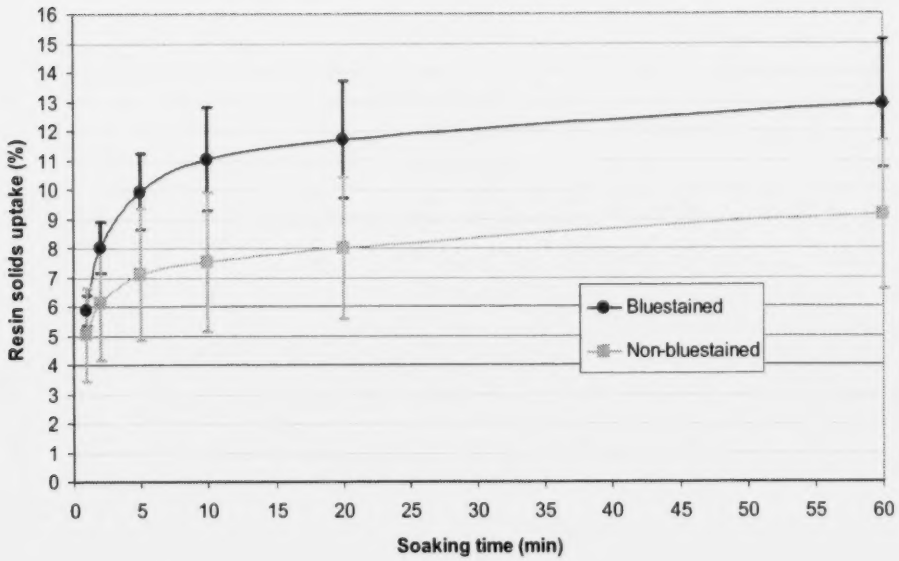


Figure 6. Resin-solids uptake within 1 h of soaking for stained and unstained veneer.

3.1.2 Relationship between resin solids uptake and dipping time for green MPB veneers

Figure 7 shows how resin solids uptake changes with soaking time from 1 to 1680 min (28 h) for stained and unstained green MPB veneer. Average veneer MC was 35.1% for stained and 27.7% for unstained veneers. Similar to the dry MPB veneers, stained MPB veneers had faster and higher resin solids uptake than unstained MPB veneers. With 28 h soaking, the average resin solids uptake was about 8.9% for the stained veneers and 5.3% for the unstained veneers. Again, this difference was largely attributed to the higher permeability of stained (sapwood) veneers.

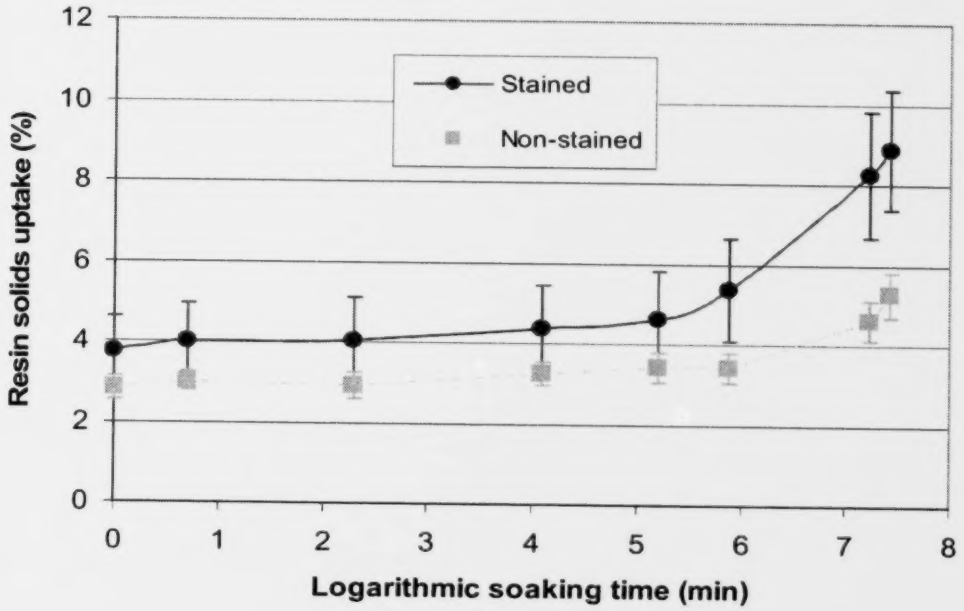


Figure 7. Changes of resin-solids uptake with soaking time for green MPB veneers.

With 10 min soaking, average resin solids uptake was 4.1% for stained and 2.9% for unstained veneers. However, both stained and unstained green MPB veneers had significantly lower resin solids uptake than the dry MPB veneers. Vacuum-pressure treatment may be needed to attain the same levels of resin uptake in the green MPB veneers as those achieved in dry MPB veneers.

3.1.3 Drying characteristics of resin- impregnated MPB veneers

Figure 8 compares the average resin solids uptake between the stained and unstained dry MPB veneer specimens (10.2 x 10.2 cm) with 1 min and 5 min dipping/soaking. Ten specimens were used for each category and dipping time. Resin-solids uptake increased with the soaking time from 1 to 5 min in both categories, but the uptake rate of the stained MPB veneers was higher.

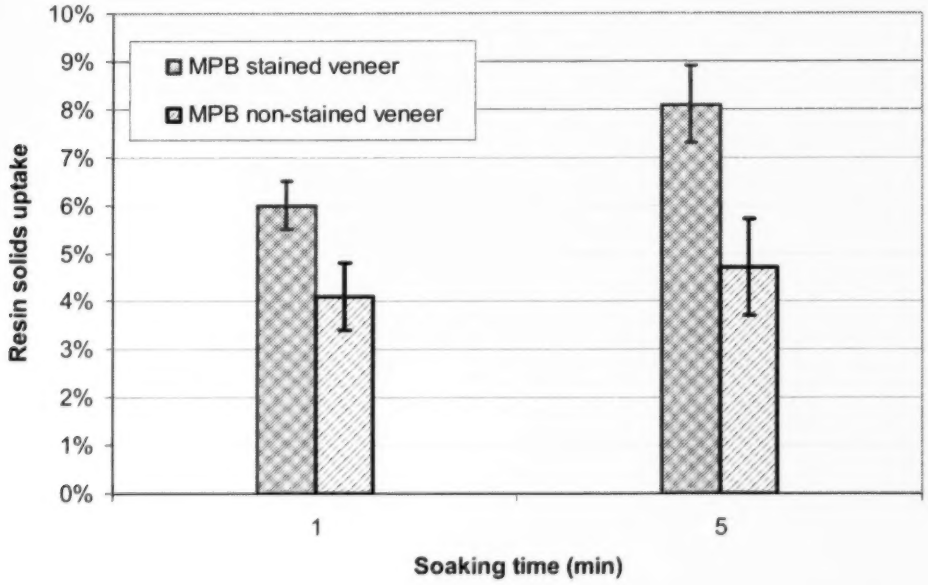


Figure 8. Resin solids uptake of stained and unstained MPB veneers at two soaking times.

Figure 9 shows the MC change of the stained MPB veneer specimens (10.2 x 10.2 cm) by air-drying and oven-drying. The initial veneer MC was about 40% after 1 min of soaking and 50%–55% after 5 min of soaking. Oven-drying reduced MC much quicker than air-drying. After 1 h of oven-drying, the average MC was about 10% for 1 min of soaking and 14% for 5 min of soaking, which were still high for panel manufacturing. But after 24 h oven-drying, the average MC was reduced to about 3%.

Figure 10 shows the MC change of air-dried and oven-dried unstained MPB veneers. The initial veneer MC was about 29% after 1 min soaking and 38% after 5 min soaking. After 1 h oven-drying, average MC was about 10%, which was almost the same for 1 or 5 min soaking, but still slightly high for panel manufacturing. But after 24 h oven-drying, the average MC was reduced to about 4%, which was slightly higher than that of the stained veneers. Unstained MPB veneers dried more slowly than the stained MPB veneers, which could be attributed to the lower permeability of the former (heartwood).

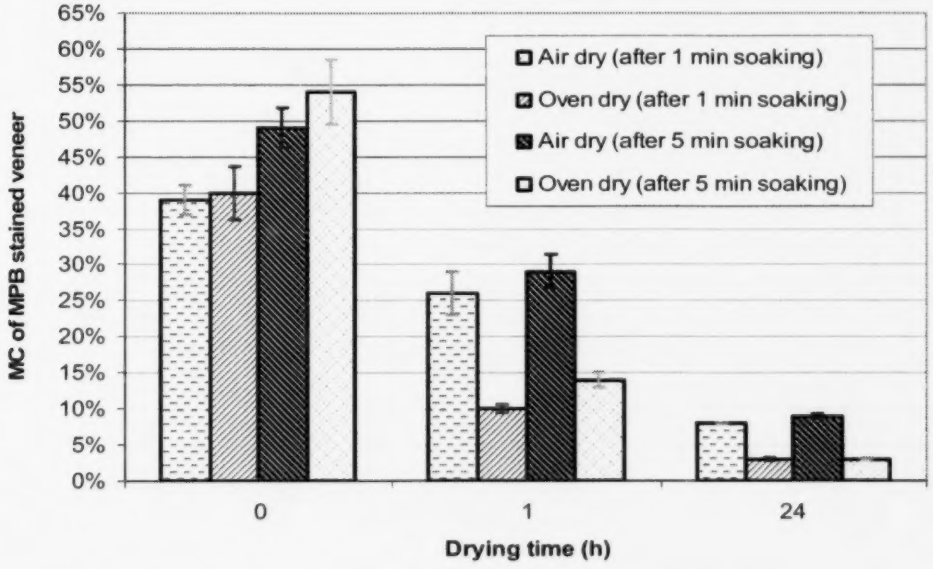


Figure 9. The MC changes of MPB-stained veneers under air-drying and oven-drying.

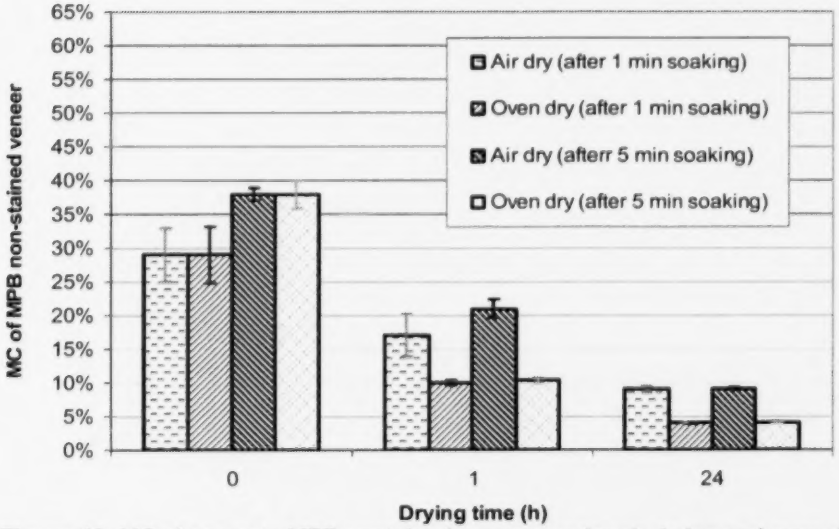


Figure 10. MC changes to MPB-unstained veneers under air-drying and oven-drying.

Figure 11 compares the drying rates for the MPB veneers (stained and unstained inclusive) under air-drying and oven-drying conditions. The specimens had an average resin solids uptake of 4.5% with a standard deviation of 1.5% after 5 min soaking in the diluted PF resin. The results showed that after 1 h of air-drying, the average veneer MC was reduced to about 19% as compared to 11% after 1 h of oven-drying, which was still high for panel manufacturing. Note that the oven-drying yielded much smaller MC variations than the air-drying. With 3 h drying, the average veneer MC was decreased to 12% from the air-drying and 5% from the oven-drying. Based on the curve of drying rates, it was determined that the oven-drying time of the MPB veneers should be from 1–3 h when soaked for 5 min.

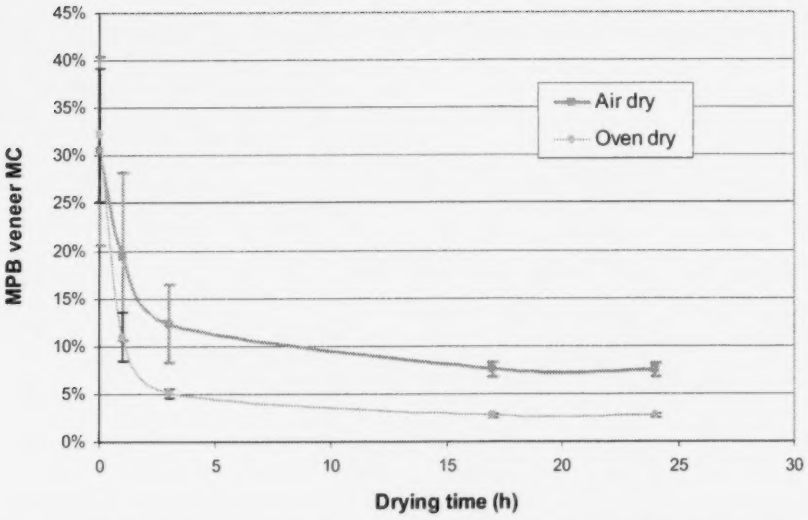


Figure 11. Comparison of drying curves of MPB veneers in two drying scenarios.

3.1.4 Manufacturing plywood from resin-impregnated MPB veneers

In addition to initial and final dry veneer MCs, veneer density also had an effect on the drying rate. The density of stained veneers was significantly higher than that of unstained veneers at $p = 0.05$ (Figure 12), which is mainly due to the difference of density between the sapwood and heartwood of lodgepole pine.

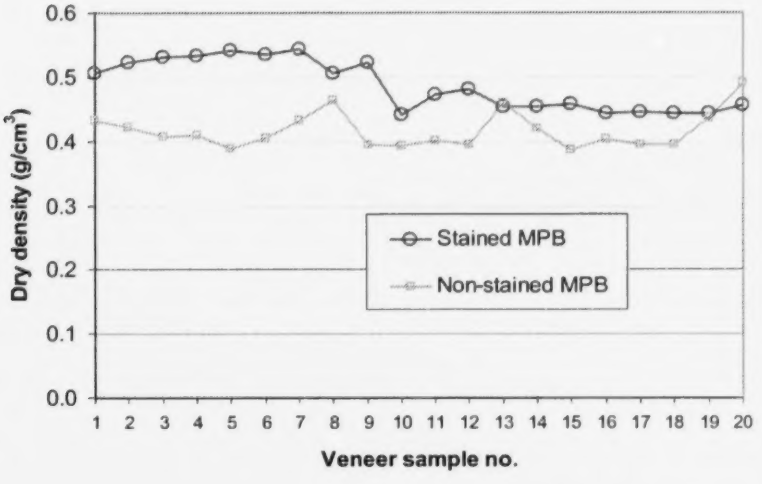


Figure 12. Comparison of density between stained and unstained MPB veneers.

Resin-solids uptake in stained MPB veneers was significantly higher than that in unstained MPB veneers (Figure 13), due to the higher permeability of the stained MPB veneers. Note that the stained veneers had a higher variation in resin-solids uptake than the unstained veneers, possibly because the area coverage of blue stain on the 40.6 x 40.6 cm stained veneer sheets varied from 30% to 100%. Also, veneer peeling often produces sheets containing both sapwood (stained) and heartwood (unstained) due to the irregular boundary of sapwood and heartwood and the inevitable centering error.

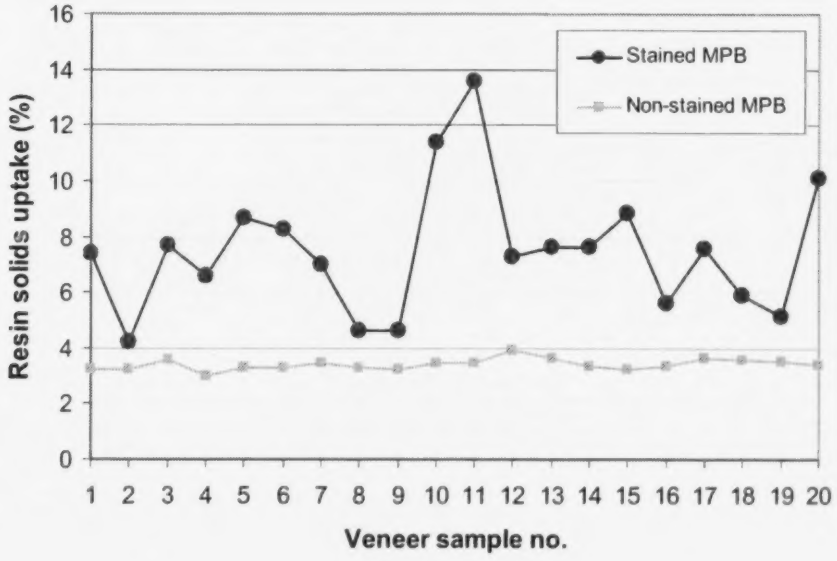


Figure 13. Comparison of resin-solids uptake between stained and unstained MPB veneers.

The average resin solids uptake for unstained MPB veneer sheets (40.6 x 40.6 cm) was 3.4% with a standard deviation of 0.2%. By comparison, the average resin solids uptake for stained MPB veneer sheets (40.6 x 40.6 cm) was 7.5% with a standard deviation of 2.3%. These mean values were slightly lower that those obtained with the small 10.2 x 10.2 cm specimens. Resin-solids uptake for stained and unstainedveneer specimens (10.2 x 10.2 cm) was 8.1% and 4.7%, respectively (Figure 8). Veneer size could have some effect on resin-solids uptake, because the small size is better for resin penetration parallel to the grain.

Figure 14 compares the final-veneer MCs between the stained and unstained MPB veneer categories. After drying, stained MPB veneers had a MC below 6% whereas the unstained counterparts had a MC over 8%. The results indicated that the stained veneers can be dried to the target MC faster despite having a higher initial MC, likely due to their higher permeability. In this study, to manufacture 5-ply plywood products without causing blisters or blows, unstained veneers were further dried for 1 h to bring their MCs to below 6% for gluing purposes.

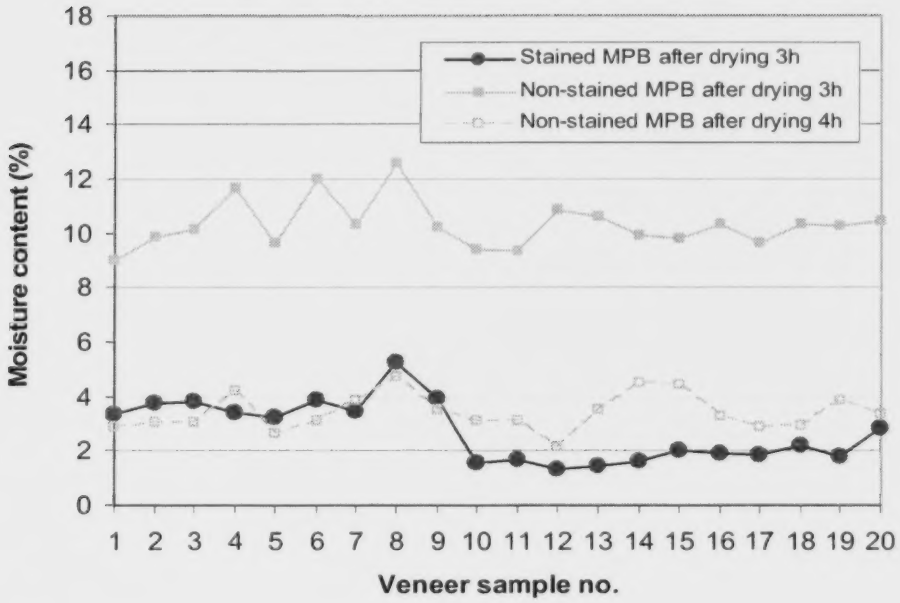


Figure 14. Comparison of drying characteristics of MPB veneers.

3.1.5 Performance and colour modification of 5-ply mountain pine beetle plywood

Table 2 summarizes the panel physical properties of 5-ply stained and unstained MPB plywood made from resin-impregnated veneers and 5-ply commercial MPB plywood (a control made from a mixture of stained and unstained veneers) sampled from an Interior British Columbia plywood mill. The final panel MC was from 7% to 8%. The stained MPB plywood had the highest specific gravity (SG), followed by mill manufactured MPB plywood and unstained MPB plywood. Based on the 48-h water soaking tests, there was a statistically significant difference in the thickness swell between the unstained MPB plywood made from treated veneers and mill manufactured MPB plywood at $p = 0.05$, while they yielded similar water absorption. By comparison, the stained MPB plywood made from treated veneers yielded larger water absorption and thickness swell than the mill manufactured MPB plywood, likely because the permeability of the stained MPB veneers is significantly higher than that of the unstained MPB veneers. In general, the volume breakdown of stained and unstained veneers is approximately 50:50. On average, the thickness swell of MPB plywood made from treated veneers in the lab was 5.9%, which was about 0.6% lower than that of the control MPB plywood. The result indicated that through resin impregnation, the dimension stability of plywood products can be improved.

Table 2. Comparison of panel physical properties between three plywood products.

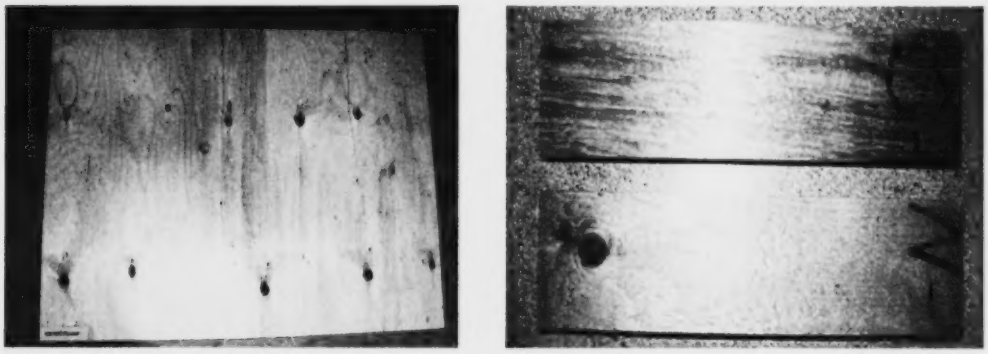
5-ply plywood	Glue type	Panel thickness	Panel MC	Panel SG	Dimensional stability after 48 h water soaking (%)		Equivalent resin solids uptake (%)
		(mm)	(%)		WA	TS	
Stained MPB	Resin treatment followed by glue application	15.88	7.1	0.545	61.4	6.8	9.8
Unstained MPB		16.18	7.9	0.455	52.6	4.9	5.7
Average		16.03	7.5	0.500	57.0	5.9	7.8
Mixed MPB (control)	No resin impregnation	15.04	7.4	0.477	53.0	6.5	2.3

Table 3 summarizes the panel-gluebond quality, hardness and parallel ply bending performance for 5-ply stained and unstained MPB plywood made from resin-impregnated veneers and 5-ply commercial MPB plywood (a control made from a mixture of stained and unstained veneers). Results showed that the shear strength and percentage wood failure of the MPB plywood made from resin-impregnated veneers were significantly higher than those of the control MPB plywood at $p = 0.05$. Compared with those of control mixed MPB plywood, the hardness and parallel-ply bending MOE and modulus of rupture MOR of stained MPB plywood were also significantly higher at $p = 0.05$. However, this improvement in hardness and parallel-ply bending performance was not observed for unstained MPB plywood. This could be mainly due to the lower level of resin-solids uptake and lower density values of unstained MPB veneers.

Table 3. Comparison of panel-gluebond quality and bending performance.

5-ply plywood	Glue type	Plywood gluebond quality		Hardness (N)	Parallel-ply bending	
		Shear strength (psi)	Wood failure (%)		MOR (psi)	MOE (10^6 psi)
Stained MPB	Resin impregnation followed by glue application	232	93.0	349 (27.6)	11196	1.33
Unstained MPB		236	98.0	264 (14.7)	7215	0.92
Average		234	95.5	307	9206	1.13
Mixed MPB (control)	No resin impregnation	136	80.6	268 (34.1)	8309	1.15

Figure 15 shows commercial MPB plywood (mill-manufactured without resin impregnation) and laboratory-made stained (upper) and unstained (lower) MPB plywood made from veneers impregnated with low MW PF resin. Low MW PF resin used to impregnate veneers clearly did not mask the blue stain.



a) Mill-made MPB plywood b) Lab-made MPB plywood

Figure 15. The appearance of mill and laboratory made MPB plywood.

Figure 16 quantitatively compares colours of mill- and laboratory-made MPB plywood panels. With no resin impregnation, stained MPB wood appeared darker and tended to be blue. Three colour components were similar between the unstained MPB wood and mill control MPB plywood. Thus, the masking effect of blue (stain) colour from this resin was not effective. A new PF resin needs to be developed to successfully modify the blue stain colour in the MPB wood.

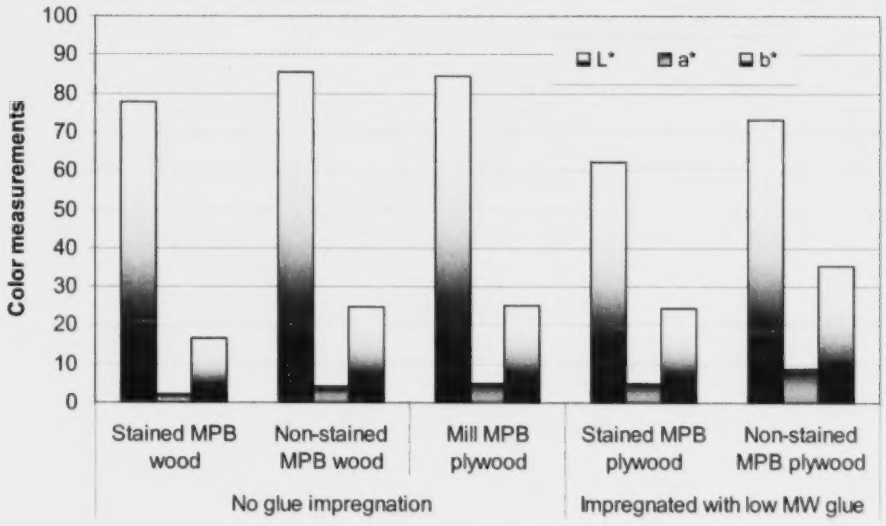


Figure 16. The comparison of colour index between MPB plywood panels.

3.2 Value-added plywood from MPB veneers impregnated with a new PF resin

3.2.1 The relationship between resin solids uptake and dipping time

Figure 17 shows changes in resin-solids uptake with dipping/soaking time for five types with the new PF resin developed based on the average of ten 10.2 x 10.2 cm specimens. There were roughly three groups of resin-solids uptake: stained MPB had the fastest and highest resin-solids uptake, followed by aspen/white spruce, and unstained MPB/control lodgepole pine. After soaking for 24 h, resin uptake of stained MPB veneers was about 37%, about twice that (18%) of unstained MPB veneers.

Figure 18 is the magnified resin-solids uptake curve over the first 30 min soaking. It can be seen that the rate of resin uptake was faster at the first 10 min, then tended to level off. With merely 5 min soaking, the resin-solids uptake was more than 16.0% for the stained MPB veneers as compared to 8.3% for the unstained MPB veneers. To increase the treatment efficiency while reducing the cost, soaking MPB veneers in the new PF resin for 5 min seemed to be optimum.

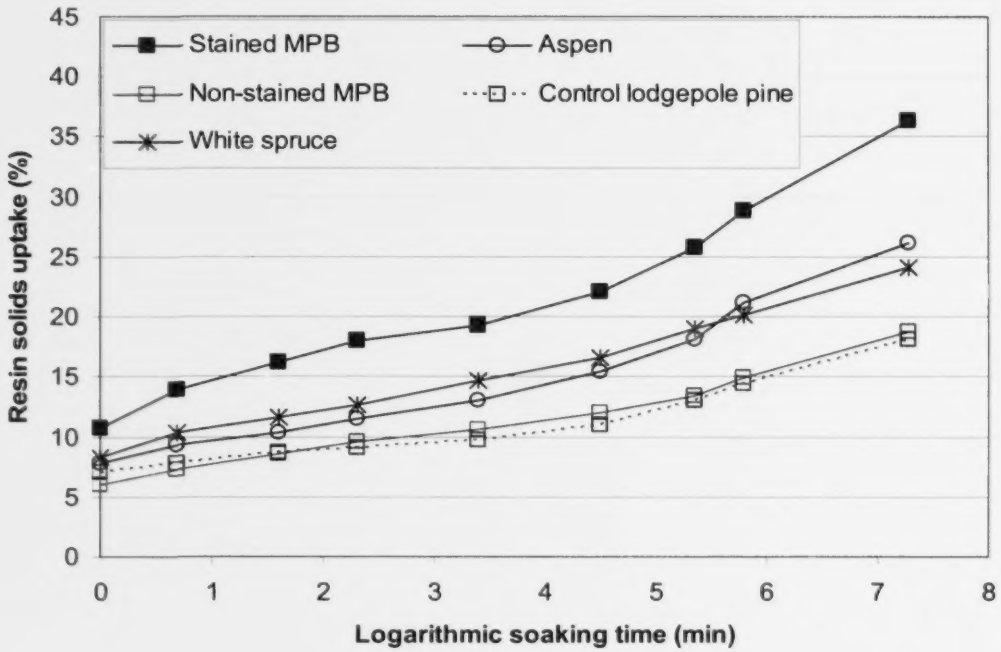


Figure 17. The relationship between resin-solids uptake and soaking time.

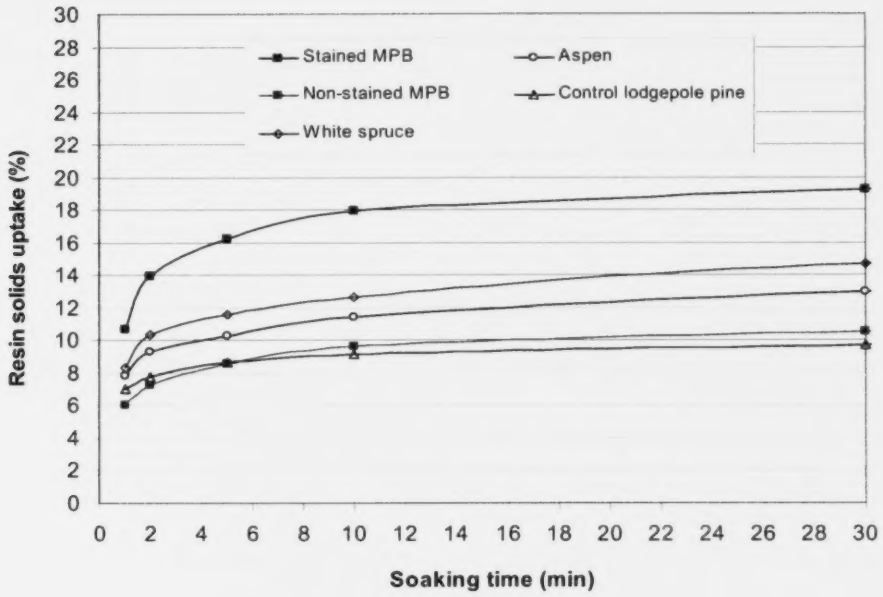


Figure 18. Resin-solids uptake at an early soaking stage.

3.2.2 Drying of resin-impregnated MPB veneers

Figure 19 compares stained and unstained veneer MC and resin-solids uptake after 5 min dipping/soaking and MC after 1 h oven-drying. After 5 min resin soaking, the average veneer MC was about 39% for stained and 28% for unstained MPB veneers. The actual resin-solids uptake was about 14.3% for the four stained MPB veneer specimens as compared to 9.7% for the four unstained counterparts. After 1 h of oven-drying, the average MC was 15.8% for the stained veneers and 9.5% for the unstained veneers. These final MC levels were slightly high for panel manufacturing.

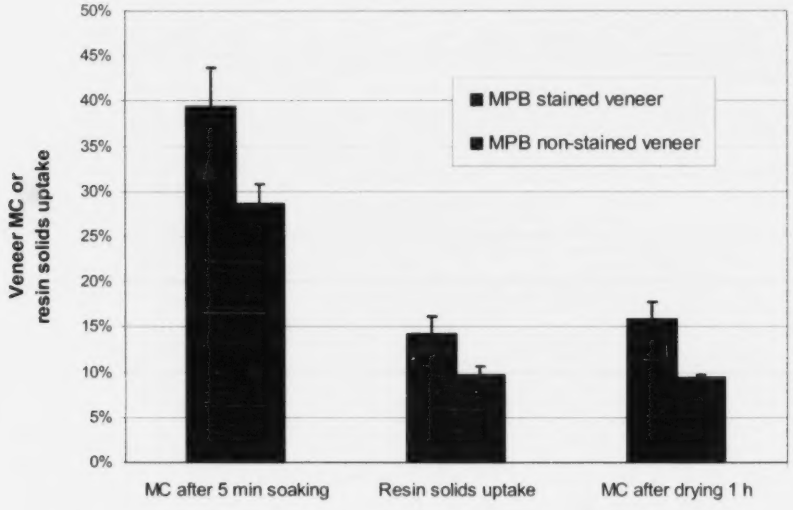


Figure 19. Changes of resin-solids uptake and MC of MPB veneers impregnated with the new PF resin.

3.. .3 Resin impregnation of 40.6 x 40.6 cm veneers

After 5 min soaking, spruce veneers had the highest percent resin-solids uptake, followed by stained MPB, aspen, control lodgepole pine, mixed MPB, and unstained MPB veneers (Figure 20), due to spruce having the lowest wood density. In terms of actual weight gain (water plus resin solids), the stained MPB veneers remained the highest. Compared to the mixed MPB, unstained MPB and control lodgepole pine veneers, stained MPB veneers had significantly higher resin-solids uptake. Average resin-solids uptake was about 10.0% for the stained 40.6 x 40.6 cm sheets, which was lower than 14.3% measured from 10.2 x 10.2 cm specimens. This discrepancy was mainly for two reasons: 1) the 40.6 x 40.6 cm sheets were not 100% covered by stain, and 2) the resin penetrated relatively easier in the small sheets along the grain direction.

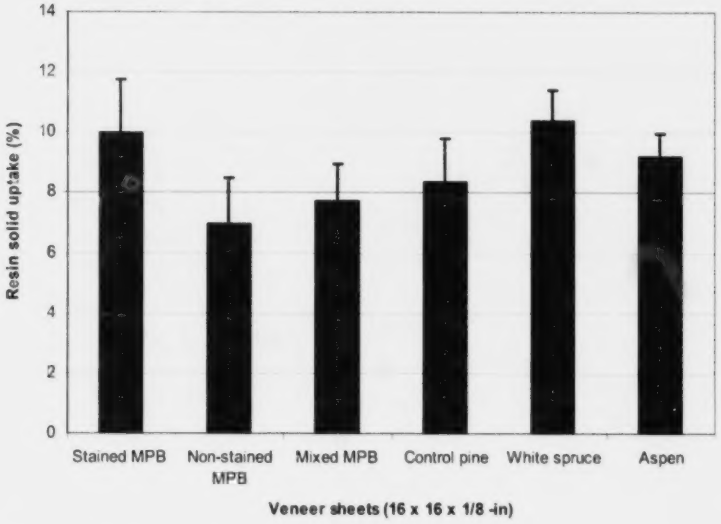


Figure 20. Comparison of resin-solids uptakes.

For all six veneer types, 2 h oven-drying yielded MC suitable for adhesive bonding (Figure 21).

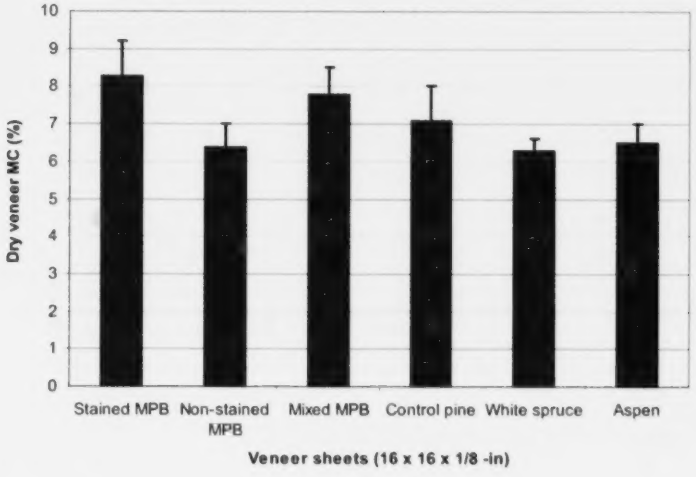


Figure 21. Final-veneer MC after 2 h oven-drying.

3.2.4 Comparing performance of 5-ply plywood made from different species

Table 4 summarizes the physical properties of 5-ply plywood made from six veneer types impregnated with the new PF resin. Using this resin obviated further glue applications after drying. On average, white spruce plywood had the highest percent resin-solids uptake, followed by stained MPB, aspen, lodgepole pine, mixed MPB and unstained MPB. Panel thickness was well controlled. The panel MC ranged from 4.4% to 6.0%, which seemed to be slightly lower than 7%–8% from the mill produced mixed MPB plywood (control). The manufacturing method seemed to have an effect on panel resin-solids uptake and dimensional stability. For both stained and unstained MPB categories, one-step manufacturing yielded higher resin-solids uptake and thickness swell but lower water absorption than two-step manufacturing. Mixed MPB plywood made from resin-impregnated veneers had higher specific gravity (SG) and better dimensional stability than control mixed MPB plywood. The 48-h water absorption and thickness swell of the latter were about 30.6% and 21.5% lower than those of the former, respectively, indicating that resin impregnation can significantly improve the dimensional stability of plywood panels.

Table 4. Physical properties of plywood panels made from resin-impregnated veneers.

5-ply plywood		Average resin solids uptake	Panel thickness		Panel MC	Panel SG	Dimensional stability*** (%)	
		(%)	(inches)	(mm)	(%)		WA	TS
One-step	Stained MPB	10.0	0.600	15.25	6.0	0.526	53.2	7.8
	Unstained MPB	7.0	0.616	15.65	5.2	0.508	43.9	6.2
	Mixed MPB	7.7	0.609	15.47	5.6	0.525	36.8	5.1
	Lodgepole pine	8.4	0.602	15.30	5.4	0.474	39.2	5.7
	White spruce	10.4	0.596	15.14	5.3	0.413	53.6	6.7
	Aspen	9.2	0.594	15.10	4.4	0.467	51.0	5.1
Two -step*	Stained MPB	9.8	0.625	15.88	7.1	0.545	61.4	6.8
	Unstained MPB	5.7	0.637	16.18	7.9	0.455	52.6	4.9
Mixed MPB**		2.3****	0.622	15.04	7.4	0.477	53.0	6.5
CSP**		2.3****	0.591	15.00	7.8	0.417	49.7	6.2

Note: * Soaking in the low MW PF resin for 5 min, followed by drying and glue application;
** Mixed MPB plywood and CSP plywood were made in the mill;
*** Soaking in the cold water for 48 h; and
**** Equivalent resin-solids uptake for 5-ply plywood with a glue application rate of 32 lb/1000 ft^2 per single glueline.

Stained MPB plywood had the fastest and highest water absorption, followed by spruce plywood; mixed MPB plywood had the lowest water absorption among all types (Figure 22). Mixed MPB plywood and aspen plywood had the lowest thickness swell, and stained MPB plywood had the highest, followed by plywoods made from spruce, unstained MPB, and control lodgepole pine (Figure 23). Stained MPB plywood was less dimensionally stable than the unstained MPB plywood, regardless of the number of manufacturing steps (Table 5). Mixed MPB plywood made from resin-impregnated veneers demonstrated the best dimensional stability, which could result from the interlocking between the stained and unstained veneers to counter thickness swell.

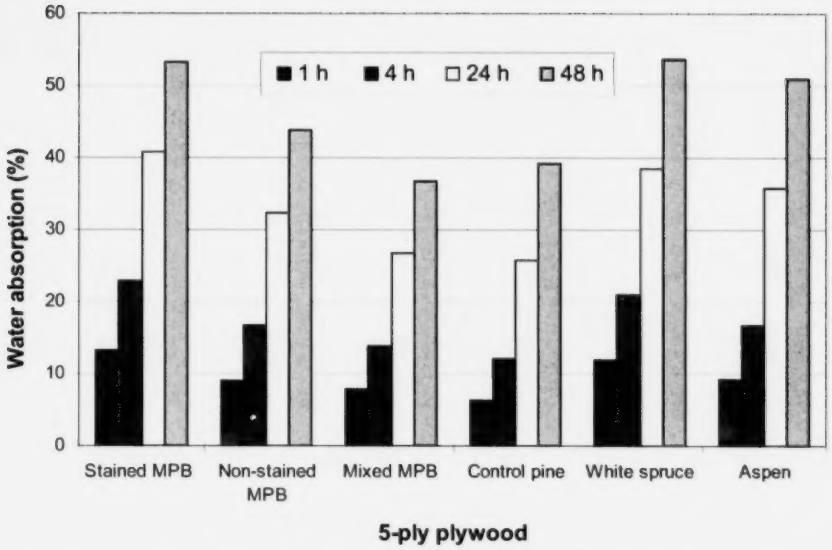


Figure 22. Water absorption of 5-ply plywood made from six veneer types.

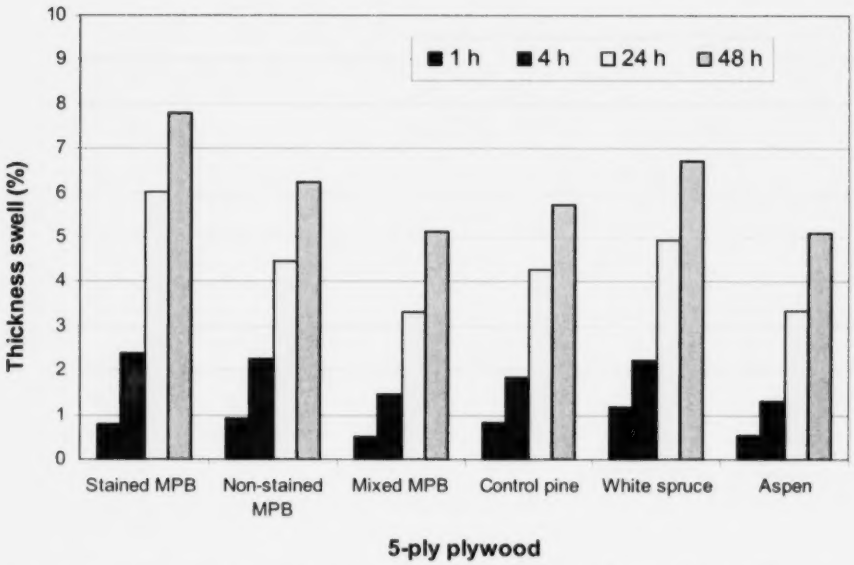


Figure 23. Thickness swell of 5-ply plywood made from six veneer types.

Table 6 shows the gluebond quality, hardness, and parallel-ply bending performance of 5-ply plywood panels made from the six veneer types. Panels made from the two-step process had significantly higher wood failure than those from the one-step process. The mixed MPB plywood generated the highest shear strength. Panels made from resin-impregnated veneers had significantly higher shear strength than mill-manufactured plywood, regardless of the manufacturing process. This high shear strength but low wood failure may be because plywood made from resin-impregnated veneers is a modified wood product. In

this case, wood is largely reinforced and hard to tear or break. As a result, the conventional gluebond quality evaluation method specified by the CSA O151 Standard may need to be revised for products made from resin-impregnated veneers (CSA 2004). Mixed MPB plywood made from resin-impregnated veneers was significantly harder than the mill-manufactured mixed MPB plywood. With resin impregnation, the stained MPB plywood was harder than the unstained MPB plywood for both one-step and two-step methods. There was no significant difference in hardness between the two methods for both stained and unstained MPB plywood at $p = 0.05$.

The one-step process generally yielded higher parallel-ply bending MOR and MOE than the two-step process for both stained and unstained MPB veneer. Mixed MPB plywood made from the one-step resin impregnation yielded much higher bending MOE and MOR than mill-produced mixed MPB plywood. Resin impregnation significantly improved plywood bending performance. Plywood made from treated stained, unstained, and mixed MPB veneers had significantly higher parallel-ply bending MOE and MOR than control mixed MPB plywood ($p = 0.05$), possibly due to 1) an additional 5.4% resin solids uptake, and 2) the potential difference in veneer density, MOE, and plywood lay-up.

Table 5. Gluebond quality, hardness and bending performance of 5-ply plywood.

5-ply plywood		Plywood gluebond quality		Hardness (N)		Parallel-ply bending	
		Shear strength (psi)	Wood failure (%)	Average	Std. Dev.	MOR (psi)	MOE (10^6 psi)
One- step	Stained MPB	214	44.6	331	21.9	11727	1.40
	Unstained MPB	193	44.0	279	14.9	8477	1.28
	Mixed MPB	243	58.3	326	15.4	10420	1.50
	Lodgepole pine	239	59.4	297	16.0	7195	1.06
	White spruce	159	49.4	248	14.6	6640	1.01
	Aspen	196	41.7	237	13.1	10282	1.31
Two -step*	Stained MPB	232	93.0	349	27.6	11196	1.33
	Unstained MPB	236	98.0	264	14.7	7215	0.90
Mixed MPB**		136	80.6	268	34.1	8309	1.15
CSP**		120	73.4	220	25.6	6946	0.96

Note: * Soaking in the low MW PF resin for 5 min, followed by drying and glue application; and
** Mixed MPB plywood and CSP plywood made in the mill.

With one-step impregnation/application using the new resin, parallel-ply bending MOE and MOR were higher for stained than for unstained MPB plywood (Table 6). Mixed MPB plywood and aspen plywood had higher bending MOE and MOR than control lodgepole pine and white spruce plywoods. Veneer properties before and after resin treatments were not measured, so the effectiveness of resin impregnation on improving bending performance was not rated. This effectiveness could be better evaluated by making control plywood from all untreated veneers, and measuring veneer sheet properties in the panel lay-up.

Panel colour of 5-ply plywood appears similar for all 6 veneer types, and the blue of stained MPB veneers was successfully masked (Figure 24).

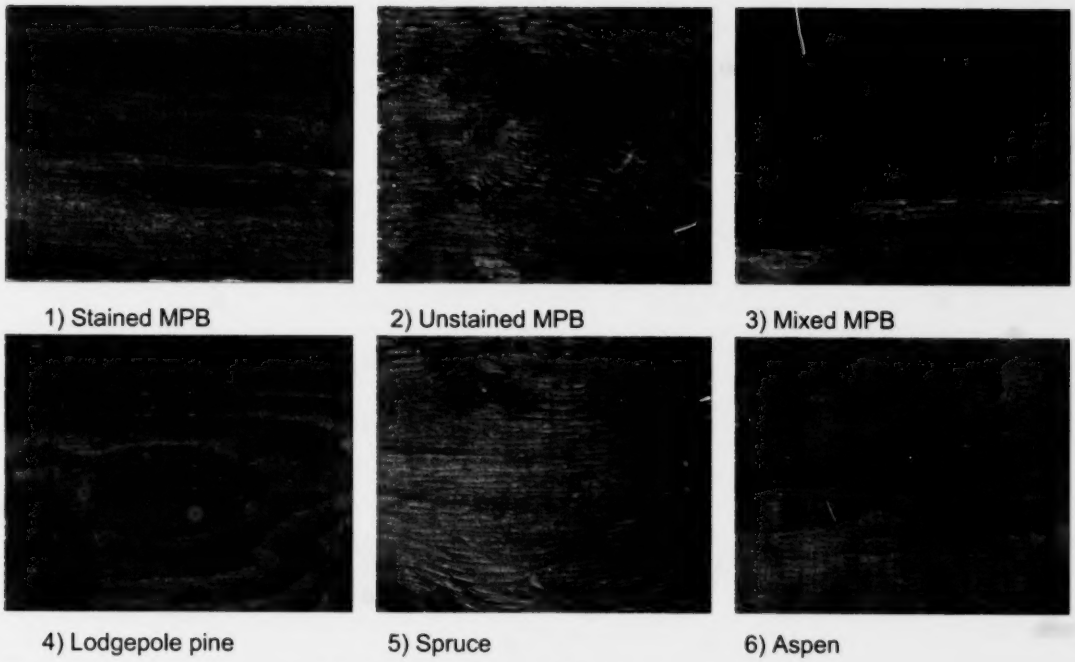


Figure 24. The appearance of 5-ply plywood panels from six types.

L*, a*, and b* colour space did not differ significantly for all 6 veneer types of 5-ply panels in (Figure 25).

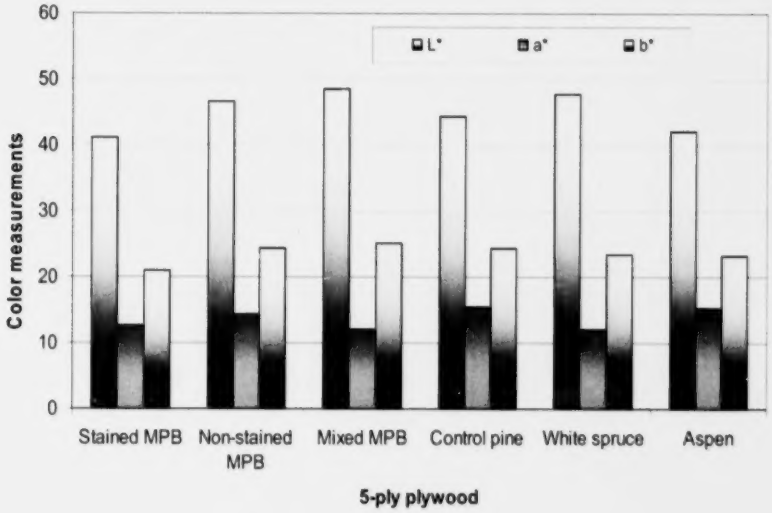


Figure 25. L, a* and b* colour measurements for 5-ply plywood.

The comparison of overall colour change ΔE* among the three plywood categories is shown in Figure 26. Without resin impregnation, the colour change was about 5 in ΔE* for the mill manufactured mixed MPB

plywood. However, with resin impregnation, the colour change appeared to be greater. The new PF resin more significant colour change than the commercial low MW PF resin. The results indicated that the new PF resin can effectively mask the blue stain in the MPB veneers with as short as 5 min dipping, and also yield consistent colour for value added plywood products made from various species.

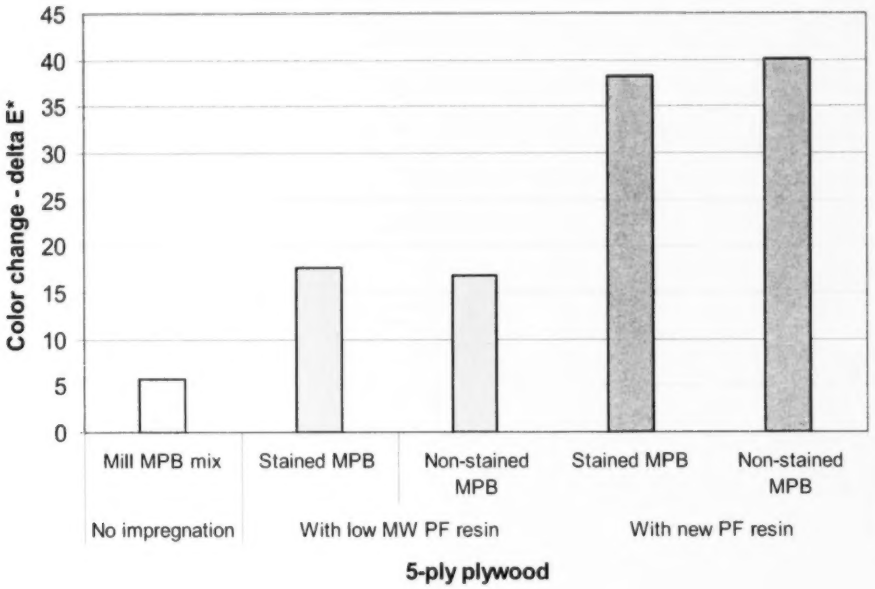


Figure 26: Comparison of color changes from different resin treatments

3.3 Performance of LVL made from MPB veneers impregnated with a new PF resin

3.3.1 Comparison of resin solids uptake among various treatments

Figure 27 compares resin-solids uptakes of stained and unstained MPB veneer categories subjected to the three treatment times. It illustrates that for all three treatments, stained MPB veneers picked up significantly more resin solids than unstained MPB counterparts. Compared to a simple dipping/soaking, vacuum-pressure treatments for 5 min significantly improved the resin-solids uptake, especially for stained veneers. However, with an additional 5 min vacuum-pressure treatment, the resin-solids uptake was increased by about 6.3% for stained veneers as compared to only 1.7% for unstained veneers.

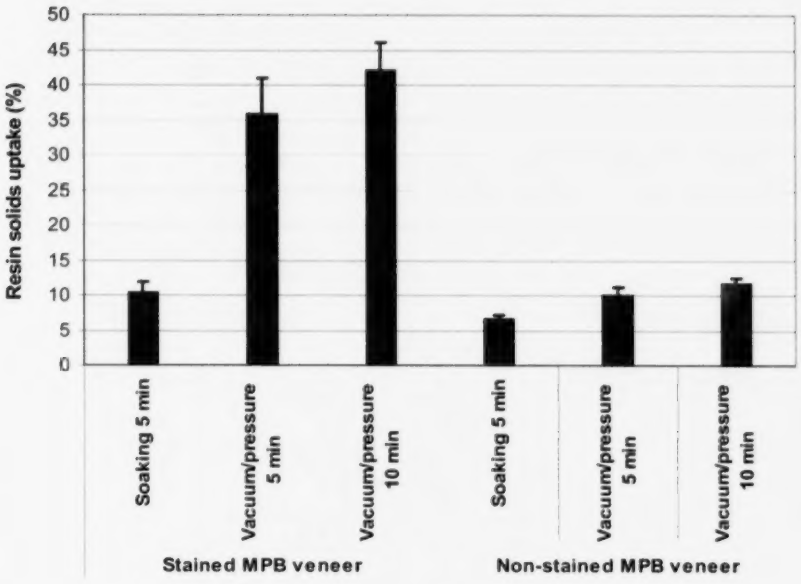


Figure 27. Effect of treatments on resin-solids uptake for stained and unstained MPB veneers.

Figure 28 compares resin-solids uptakes of stained and unstained MPB veneer categories among the three soaking times. For all three soaking treatments, stained MPB veneers had a significantly higher resin-solids uptake than unstained MPB counterparts at $p = 0.05$. The final resin-uptake levels for tests No.7 (stained) and 9 (unstained) with 1 h of soaking were increased to almost the same levels as those obtained for tests No. 8 (stained) and 10 (unstained) with 6 h soaking. The t-tests showed that there was no significant difference in the resin-solids uptake between these two treatment times for both stained and unstained MPB veneer categories at $p = 0.05$. This could be mainly due to the fact that a two-stage soaking was actually used in the case of 1 h of soaking. Namely, after soaking for 30 min, veneer sheets were taken out for a period of time to check weight gains and then soaked in the resin again to achieve a total of 1 h of soaking.

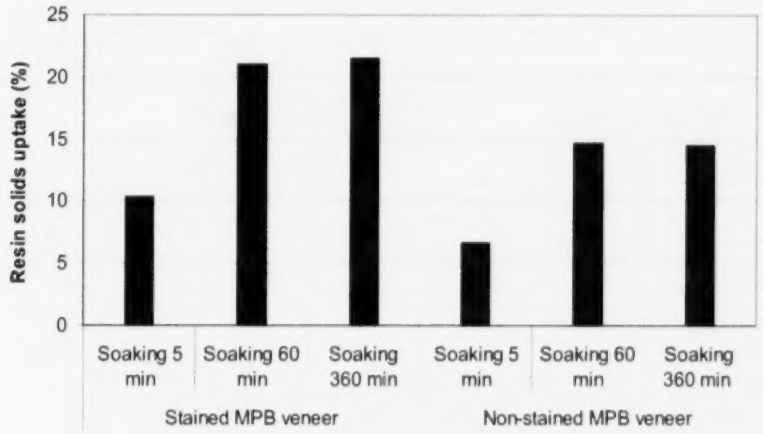


Figure 28. Resin-solids uptake of stained and unstained MPB veneers among the three soaking times.

3.3.2 Drying of MPB veneers from various treatments

Figure 29 shows the MC changes of the 15 40.6 x 30.5 cm MPB veneer sheets for both categories after 5 min soaking and 4.5 h oven-drying. The MC for stained and unstained veneers after 5 min soaking ranged from 25%–40% and 18%–24%, respectively. After 4.5 h drying, the MC stabilized to an average of about 7.5% for unstained veneers and 8.0% for stained veneers. However, the final-veneer MC of stained veneers was significantly higher than that of unstained veneers at $p = 0.05$. Without further glue applications, the final veneer MC levels from 7%–12% were seen as appropriate for LVL manufacturing.

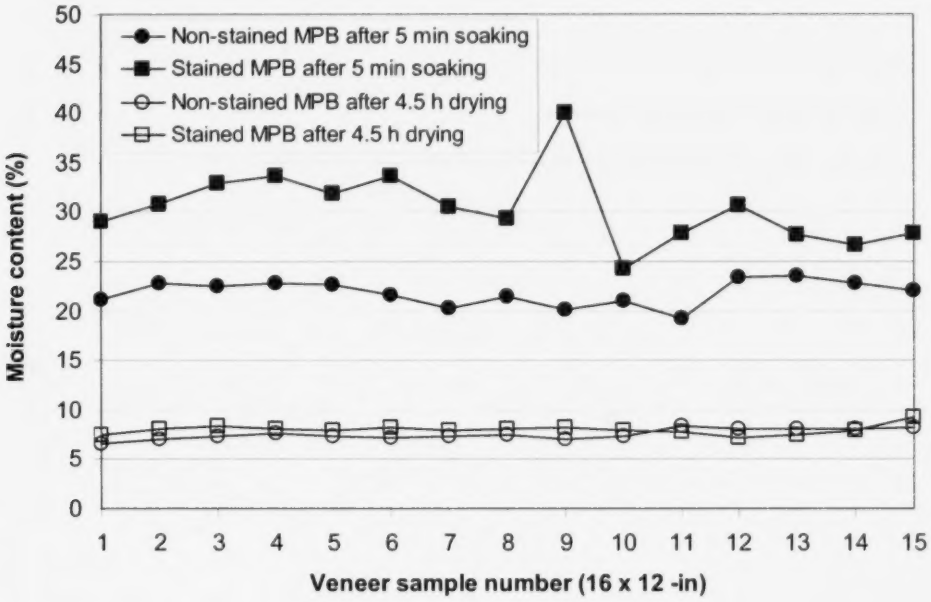


Figure 29. Changes of MPB veneer MC after 5 min soaking and 4.5 h oven-drying.

Figure 30 shows the MC changes of the fifteen 40.6 x 30.5 cm veneer sheets for each category after 5 min vacuum-pressure treatments and oven-drying. The MC after 5 min vacuum-pressure treatments ranged from 35%–90% for stained and 20%–35% for unstained MPB veneer. Accordingly, stained veneers were dried for 6 h, and unstained veneers for 5.5 h, to achieve the same final-veneer MC for gluing purposes. The average MC was 8.4% for unstained veneers after 5.5 h drying and 7.5% for stained veneers after 6 h drying. These MC levels were seen as appropriate for LVL manufacturing.

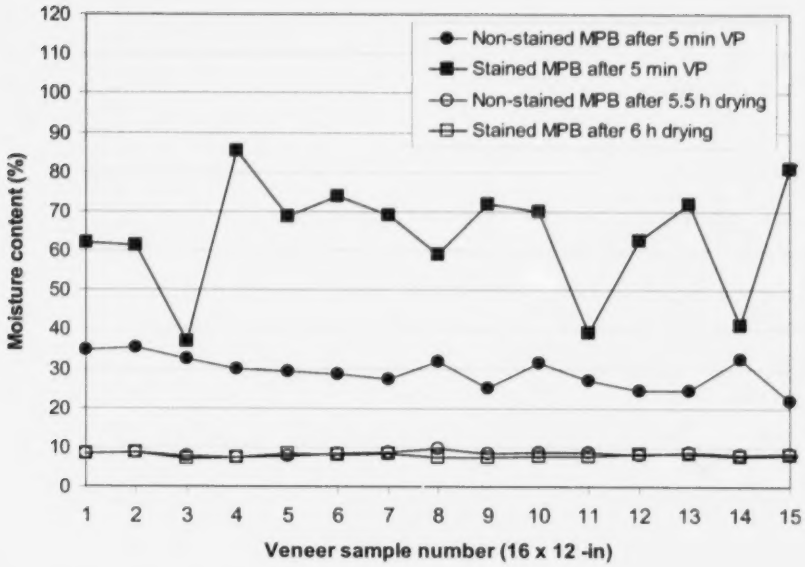

Non-stained MPB after 5 min VP
Stained MPB after 5 min VP
Non-stained MPB after 5.5 h drying
Stained MPB after 6 h drying
Moisture content (%)
Veneer sample number (16 x 12 -in)

Figure 30. Changes of MPB veneer MC after 5 min vacuum pressure and 5.5-6 h oven-drying.

Figure 31 shows the MC changes after 10 min vacuum-pressure treatments and 6 h oven-drying. The MC after 10 min vacuum-pressure was 55%–120% for stained and 30%–40% for unstained MPB veneer. After 6 h drying, average MC was 8.0% (standard deviation = 0.50%) for unstained and 7.3% (standard deviation = 0.44%) for stained veneers. Statistically, the former had a higher final MC than the latter at p = 0.05. Although stained veneers had a much higher MC than unstained veneers after resin treatments, they dried faster, likely due to their higher permeability. In addition, stained veneers had more uniform final MC than unstained veneers from sheet to sheet.

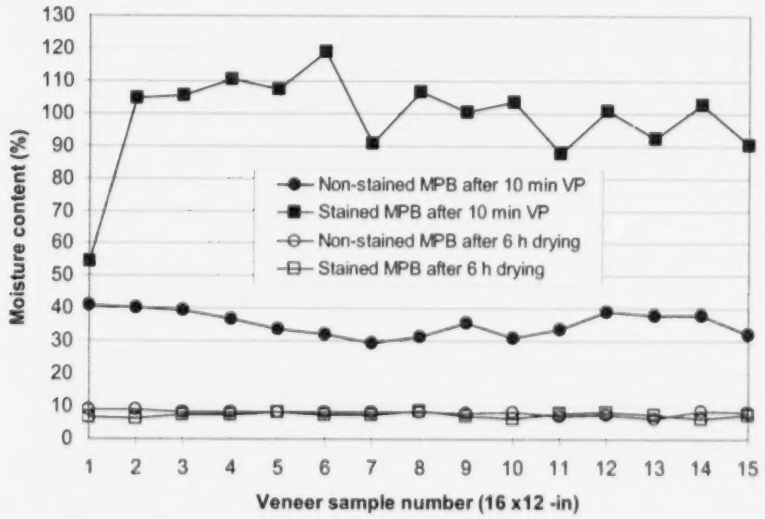

Non-stained MPB after 10 min VP
Stained MPB after 10 min VP
Non-stained MPB after 6 h drying
Stained MPB after 6 h drying
Moisture content (%)
Veneer sample number (16 x12 -in)

Figure 31. Changes of MPB veneer MC after 10 min vacuum pressure and 6 h oven-drying.

Figure 32 shows the MC changes of the fifteen 40.6 x 30.5 cm MPB veneer sheets for each category after 6 h soaking and 2 h oven-drying. The MC after 6 h soaking ranged from 40%–75% for stained and 30%–46% for unstained MPB veneer. After 2 h drying, the MC of both veneer types were still slightly higher with an average of about 18% for stained and 13% for unstained MPB veneers. Further air-drying brought MC down to about 10% before manufacturing into LVL products.

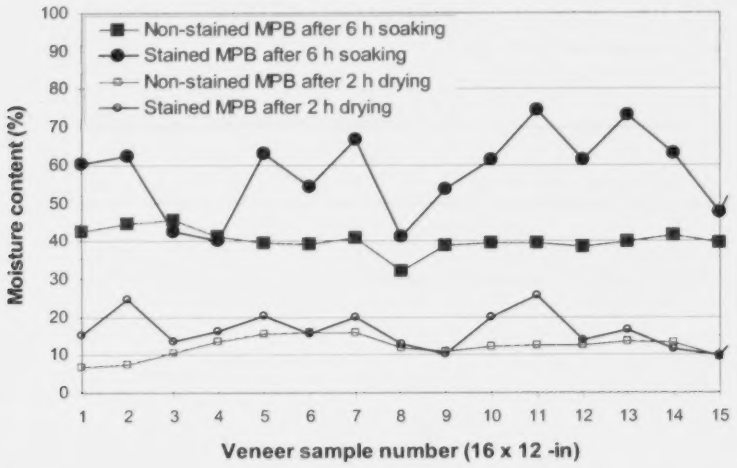

Non-stained MPB after 6 h soaking
Stained MPB after 6 h soaking
Non-stained MPB after 2 h drying
Stained MPB after 2 h drying
Moisture content (%)
Veneer sample number (16 x 12 -in)

Figure 32. Changes of MPB veneer MC after 6 h soaking and 2 h oven-drying.

3.3.3 Relationship between MPB veneer MOE enhancement and resin solids uptake

Overall, veneer MOE was boosted by the resin impregnation for all MPB 40.6 x 30.5 cm veneer sheets (Figure 33). Approximately, a 10% resin solids uptake increased veneer MOE by 8%.

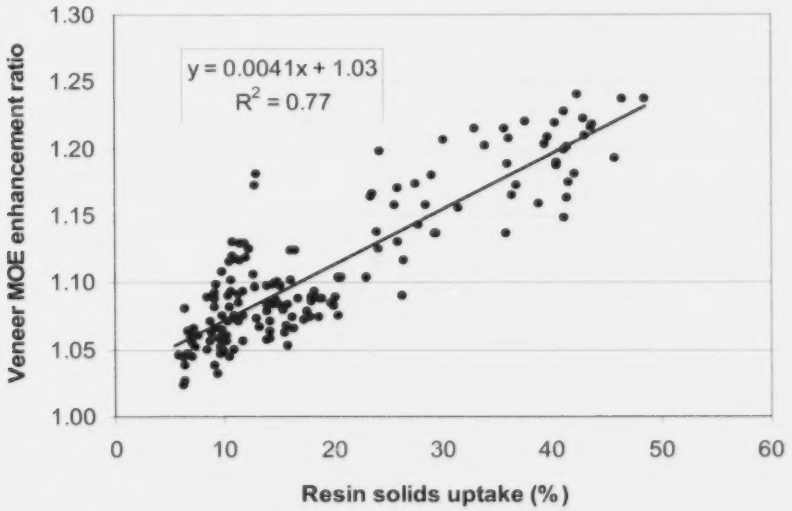


Figure 33. The correlation between MPB veneer MOE enhancement and resin-solids uptake.

The same resin-solids uptake yielded a slightly greater enhancement in veneer MOE in unstained MPB veneers than in stained veneers (Figure 34), likely due to unstained veneers' lower veneer initial density. Low-grade (density) veneers can be strengthened more easily than high-grade (density) veneers (Wang and Dai 2005, 2006).

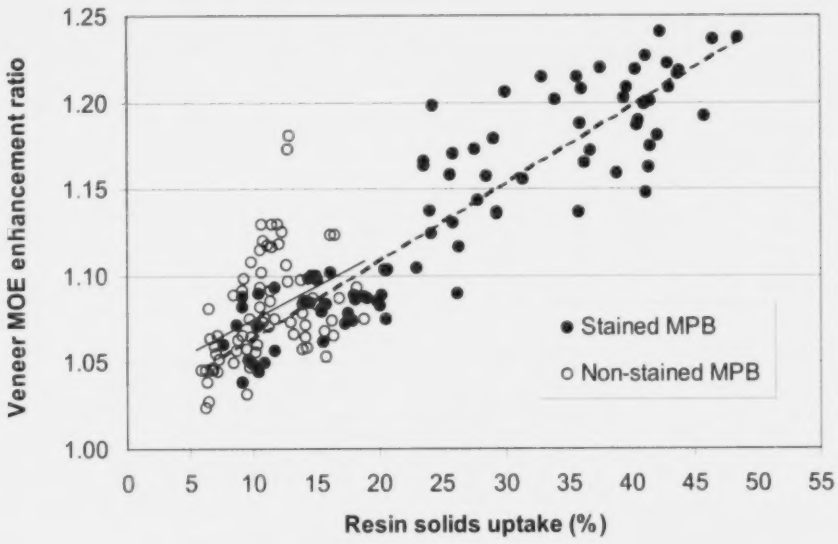


Figure 34. Veneer-MOE enhancement of stained and unstained MPB veneer.

Figure 35 shows how veneer-MOE enhancement changes with the treatment methods. The higher the resin-solids uptake, the greater the veneer MOE enhancement. As discussed earlier, for stained MPB veneers, vacuum-pressure treatments for 10 min yielded about 6.3% more resin-solids uptake than for 5 min. However, with this amount of additional resin, the veneer-MOE enhancement was not significant at $p = 0.05$. For unstained MPB veneers, vacuum-pressure treatments for 10 min yielded about 1.7% more resin-solids uptake than for 5 min. However, with this small addition of resin, the veneer-MOE enhancement was significant at $p = 0.05$. Although stained veneers were more permeable to achieve a higher resin solids uptake than unstained veneers, the veneer-MOE enhancement was not significant when the resin retention reached a certain level such as 35%. Thus, it seems to be more cost-effective to reinforce veneers at a relatively low level of resin-solids uptake to optimize veneer stiffness. In practice, an optimum resin-solids uptake should be developed specifically to the requirements of the final products.

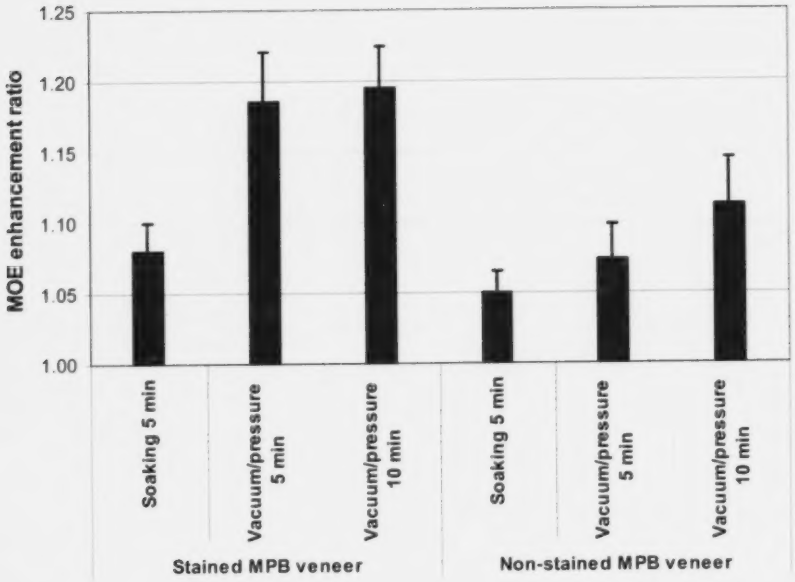


Figure 35. The enhancement of MPB-veneer MOE from different treatments.

Figure 36 shows how veneer-MOE enhancement changes with dipping/soaking times. Similarly, higher resin-solids uptake enhanced veneer MOE. Drying-soaking-drying significantly improved resin-solids uptake and, in turn, enhanced MOE. However, this method was more effective with unstained MPB veneers than stained MPB veneers. To optimize productivity, soaking 5 min was the most cost-effective for MPB LVL manufacturing, which echoes the result obtained from 5-ply MPB plywood. With merely 5 min soaking, veneer stiffness can be reinforced by 8.0% in stained and 5.0% in unstained MPB veneer.

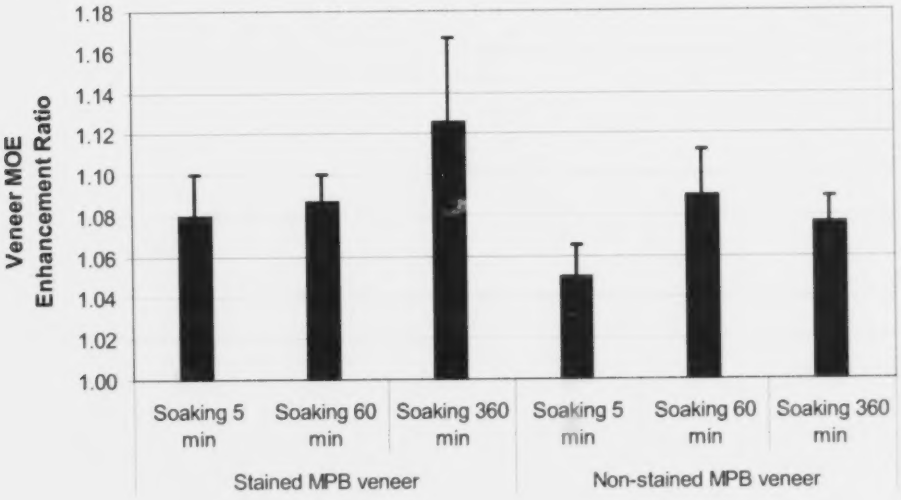


Figure 36. The enhancement of MPB-veneer MOE from different soaking times.

3.3.4 Appearance and performance of MPB LVL made from various treatments

The colour of LVL billets made from treated MPB veneers was measured by a spectrophotometer CM-600d using colour index L*, a*, and b* (Figure 37). All treatments masked the blue stain. With only 5 min of dipping/soaking, no significant difference existed in the colour index b* (indication of blue and yellow) between stained and unstained MPB LVL at $p = 0.05$, indicating it successfully masks the stain.

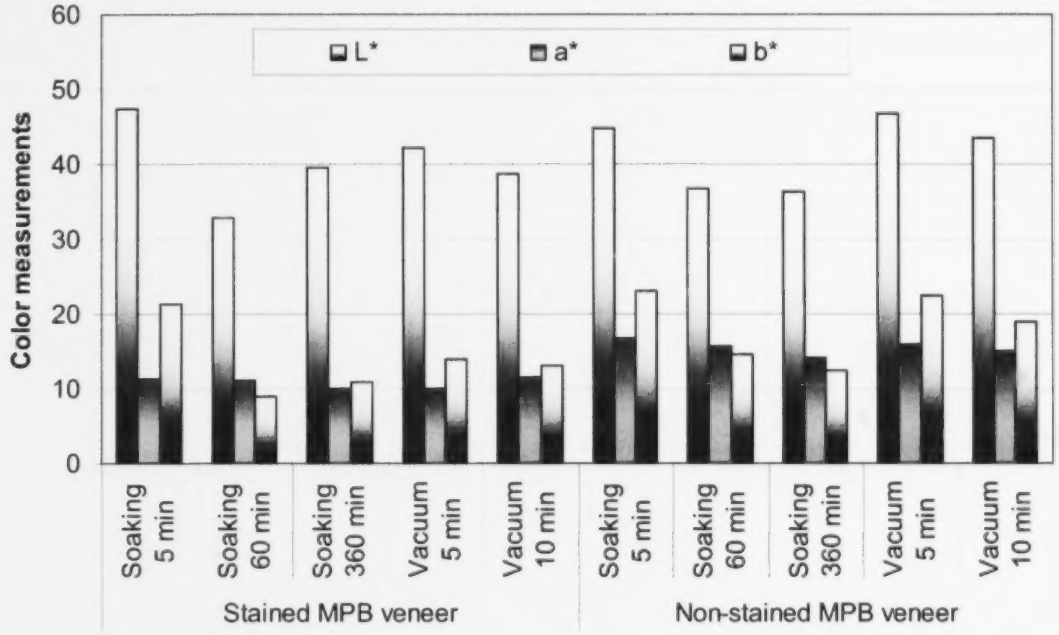


Figure 37. The colour components of MPB LVL billets made from different treatments.

Table 6 summarizes the veneer properties before and after treatments, resin-solids uptake and average veneer MOE enhancement from different treatments. After resin treatments, both veneer density and MOE were increased to some extent depending on the treatment method and time. Note that for regular plywood or LVL without resin impregnation, the actual resin-solids uptake was about 2.3%–2.5% for 5-ply constructions. By deducting this amount of resin required for interfacial veneer-to-veneer bonding, the extra resin-solids uptake from 5 min of dipping/soaking was only about 8.0% for stained and 4.3% for unstained MPB veneers, but it enhanced veneer MOE by about 7.9% and 5.4%, which means that a 1% resin-solids uptake could result in approximately a 1% veneer-MOE enhancement. Of course, this enhancement was slightly greater with the lower density veneers—in this case, unstained MPB veneer. This phenomenon was also discovered in the early work by the authors (Wang and Dai 2005).

With an increase of soaking time and, in turn, resin retention, the ratio of veneer-MOE enhancement was less significant than at the lower resin retention level. The low molecular weight (MW) PF resin may first penetrate cell walls (Kamke and Lee 2007) or affix to them, but once the resin retention reaches a certain level, the extra resin mainly fills the cell cavities instead of the cell walls and will not contribute to the veneer-MOE enhancement. Although test No.3 gained about 6.3% more resin solids than No.2, the final MOE enhancement stayed almost the same at about 18%. Further research is necessary to: 1) establish the most economical resin-solids uptake for veneer-MOE enhancement, and 2) examine the resin penetration in the cell walls in terms of the retention level with SEM technology (Konnerth et al. 2008).

For stained MPB veneers, the resin-solids uptake in test No. 7 was about twice that of test No. 1 (Table 6); however, the difference in veneer MOE enhancement ratio was < 1%. For the unstained MPB veneers, the resin-solids uptake in test No.10 was 7.8% higher than that of test No. 4; however, the difference in veneer MOE enhancement ratio was < 2%. The results demonstrated that for MPB veneers, 5 min of dipping/soaking was very cost-effective in terms of treatment efficiency and property enhancement.

Table 6. Resin-solids uptake properties of MPB-veneer before and after treatment

Test no.	MPB veneer category	Treatment	Veneer before treatment		Resin solids uptake (%)	Veneer after treatment		MOE enhancement ratio
			Density (g/cm^3)	MOE (10^6 psi)		Density (g/cm^3)	MOE (10^6 psi)	
1	Stained	Soaking 5 min	0.480	1.96	10.3	0.533	2.11	1.079
2	Stained	Vacuum pressure 5 min	0.485	1.92	35.8	0.672	2.26	1.181
3	Stained	Vacuum pressure 10 min	0.487	1.89	42.1	0.710	2.23	1.182
4	Unstained	Soaking 5 min	0.448	1.65	6.6	0.479	1.74	1.054
5	Unstained	Vacuum pressure 5 min	0.491	1.76	9.9	0.558	1.89	1.073
6	Unstained	Vacuum pressure 10 min	0.508	1.69	11.6	0.597	1.87	1.110
7	Stained	Soaking 1 h	0.495	2.02	21.0	0.615	2.19	1.085
8	Stained	Soaking 6 h	0.444	1.76	21.4	0.551	1.97	1.119
9	Unstained	Soaking 1 h	0.481	1.79	14.7	0.564	1.95	1.090
10	Unstained	Soaking 6 h	0.448	1.54	14.4	0.523	1.65	1.070
Control	13-ply MPB LVL	No resin impregnation	0.460*	1.82	2.5**	N/A	N/A	N/A

Note: * Refer to Wang and Wharton (2008). The density value was calibrated to a 6% MC level.
** Equivalent resin-solids uptake from the glue application.

Table 7 summarizes the physical properties of 5-ply MPB LVL made from various treatments. The final LVL MC ranged from 5% to 8%. The 5-ply LVL compression ratio (CR) was from 5% to 8%, which was equivalent to that from 5-ply MPB plywood. From a dimensional-stability perspective, the short term (24-h) water absorption (WA) and thickness swell (TS) of unstained MPB LVL were much less than those of stained MPB LVL. Compared with the control 13-ply MPB LVL made from mixed stained and unstained MPB veneers, the unstained 5-ply MPB LVL exhibited much smaller WA and TS but the stained counterpart seemed to yield the same level of WA and TS from 24-h water soaking. However, for each treatment condition, the average WA and TS values of 5-ply MPB LVL from the two categories were significantly smaller than those of 13-ply control MPB LVL. These results demonstrated that the dimensional stability of MPB LVL can be improved through the resin impregnation of MPB veneers.

Table 7. Physical properties of 5-ply MPB LVL made from different resin treatments.

Test no.	MPB veneer category	Treatment	5-ply MPB LVL					
			Thickness (mm)	SG	MC (%)	CR (%)	24 h soaking	
							WA (%)	TS (%)
1	Stained	Soaking 5 min	15.45	0.551	6.0	8.1	42.3	7.1
2	Stained	Vacuum pressure 5 min	14.52	0.664	6.8	8.1	42.4	5.2
3	Stained	Vacuum pressure 10 min	14.73	0.679	7.2	7.5	44.8	6.9
4	Unstained	Soaking 5 min	16.35	0.483	5.2	5.7	33.9	5.3
5	Unstained	Vacuum pressure 5 min	15.83	0.546	6.6	5.9	28.0	3.8
6	Unstained	Vacuum pressure 10 min	15.83	0.569	6.6	5.1	30.6	3.8
7	Stained	Soaking 1 h	15.44	0.601	7.8	7.3	39.6	7.7
8	Stained	Soaking 6 h	15.07	0.542	7.5	8.5	50.8	7.0
9	Unstained	Soaking 1 h	15.91	0.556	7.4	7.8	21.6	4.0
10	Unstained	Soaking 6 h	15.78	0.514	6.9	7.8	27.2	2.8
Control	13-ply MPB LVL	No resin impregnation	37.50	0.496	6.7	10.1	48.5	6.7

Table 8 summarizes the mechanical properties of 5-ply MPB LVL made from different resin treatments. The MOE in flatwise bending of MPB LVL made from various resin treatments was higher than the MPB-veneer MOE after resin treatments. The ratio of MOE between LVL and veneer ranged from 1.01 to 1.16, which was mainly governed by how veneer sheets were placed in the lay-up of the billet. In general, the stronger the face and back (layers), the higher the flatwise bending MOE and MOR. With merely 5 min of dipping/soaking for the MPB veneers, the flatwise bending MOE of 5-ply LVL achieved 2.45 and 1.95 million psi for the stained and unstained categories, respectively, meeting 2.2 E and 1.9 E LVL market requirements. Note that these two LVL grades were one grade higher than commercial 2.0 E and 1.8 E LVL grades, respectively. The results demonstrated that with 5 min of resin dipping/soaking, high performance LVL products can be manufactured from the MPB veneers. Note that with vacuum-pressure

treatments and longer dipping/soaking, the final flatwise bending MOE and MOR of 5-ply MPB LVL were not improved significantly. As well, compared to the control 13-ply MPB LVL, the shear strength of the 5-ply MPB LVL was comparable in the L-X direction but was significantly higher in the L-Y direction. In addition, the hardness of the 5-ply MPB LVL with 5 min resin dipping/soaking was much higher than that of the control 13-ply MPB LVL. These results demonstrated that with 5 min resin dipping/soaking, high performance LVL products can be developed from the MPB veneers with improved hardness and shear strength.

Table 8. Mechanical properties of 5-ply MPB LVL made from different resin treatments.

Test no.	MPB veneer category	Treatment	5-ply MPB LVL					
			Flatwise bending		LVL/veneer MOE ratio	Shear strength (psi)		Hardness
			MOE (10^6 psi)	MOR (psi)		L-X	L-Y	(N)
1	Stained	Soaking 5 min	2.45	14422	1.16	831	1614	332.4
2	Stained	Vacuum pressure 5 min	2.57	9618	1.14	734	1465	270.6
3	Stained	Vacuum pressure 10 min	2.53	8324	1.13	792	1574	326.9
4	Unstained	Soaking 5 min	1.95	9559	1.12	718	1320	292.2
5	Unstained	Vacuum pressure 5 min	2.10	13375	1.11	989	1618	266.1
6	Unstained	Vacuum pressure 10 min	1.89	11560	1.01	866	1699	334.4
7	Stained	Soaking 1 h	2.42	15690	1.11	1668	2298	291.7
8	Stained	Soaking 6 h	2.09	12537	1.06	1012	1684	331.7
9	Unstained	Soaking 1 h	1.98	13863	1.02	1449	1784	380.0
10	Unstained	Soaking 6 h	1.73	11978	1.05	1280	1658	277.8
Control	13-ply MPB LVL*	No resin impregnation	1.83	9716	1.01	798	1073	260.0

Note: *Refer to Wang and Wharton (2008). The LVL was made from mixed MPB veneers without stress grading.

3.4 Durability

3.4.1 Perforator test results

Table 9 summarizes the formaldehyde content results from samples with different levels of resin retention. The European free formaldehyde limits are 8.0 mg/100 g (max) for the E1 category and 8.1 to 30 mg/100 g for the E2 category. All samples fitted easily in the E1 category, emitting 10 times less than the fixed limit. Deviations between the duplicates for some samples were quite high, but can be explained by the very low emission of the samples. These results indicated that for EWPs made from the resin impregnated MPB veneers, the ageing procedures were unnecessary prior to the decay-resistant tests. The resulting EWPs, regardless of the high resin retention, were green or environmentally friendly, as their formaldehyde content was the same as that of wood veneer itself (background level).

Table 9. Formaldehyde-content results according to EN 120:92.

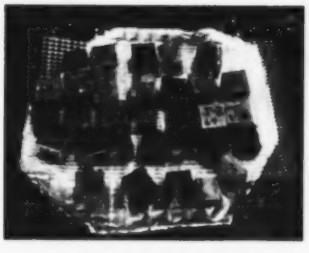
Case	Wood sample	Average MC (%)	Perforator values at test (mg/100g oven-dry board)	Corrected perforator values at 6.5% MC (mg/100g board)	Average perforator value at 6.5% MC (mg/100g board)	Rating category	Deviation of test samples (%)
1	Untreated veneer (3.2 mm)	5.92	0.37	0.40	0.41	E1	5.89
			0.39	0.42			
2	5-ply 1.6 cm mill made plywood	6.88	0.38	0.36	0.38	E1	8.60
			0.42	0.40			
3	5-ply 1.6 cm LVL (12% resin solids uptake)	5.86	0.48	0.52	0.61	E1	25.67
			0.65	0.71			
4	5-ply 1.6 cm LVL (25% resin solids uptake)	6.32	0.32	0.33	0.31	E1	10.65
			0.29	0.30			
5	5-ply 1.6 cm LVL (38% resin solids uptake)	6.51	0.71	0.70	0.62	E1	30.69
			0.54	0.54			

3.4.2 Decay resistance

Figure 38 shows various blocks after being exposed to the brown-rot fungus (*Coniophora puteana*) for 12 weeks in a soil block decay test. Most of the solid wood blocks fell apart (case a). MPB plywoods (case b), either mill or laboratory made, were less damaged, and most of the MPB LVL (case c) remained intact.

a) Control wood blocks

b) MPB plywood



c) MPB LVL

Figure 38. Various blocks after exposure to *C. puteana* for 12 weeks.

Table 10 summarizes the weight losses, MCs and retention of MPB plywood and MPB LVL (with various PF resin treatment conditions) as well as control wood blocks.

Table 10. Soil block decay test results exposed to a brown-rot fungus for 12 weeks.

Product	Stain category	Treatment	Total PF resin solids uptake (%)	Equilibrium MC (%)	Corrected weight loss (%)
MPB plywood	Unstained	Dip in a low MW PF for 5 min, then dry and apply a PF glue mix	6.0	115.0 (17.1)*	45.3 (11.5)
	Stained		10.0	96.2 (12.8)	17.9 (15.7)
MPB LVL	Unstained	Dip for 5 min (new PF resin)	6.6	94.7 (22.8)	50.9 (5.8)
	Stained		10.8	80.0 (18.3)	38.5 (20.2)
	Unstained	Dip for 6 h (new PF resin)	14.5	75.6 (18.4)	2.6 (2.1)
	Stained		21.4	92.3 (15.1)	0.6 (0.8)
	Unstained	Vacuum- pressure 5 min (new PF resin)	10.0	106.2 (13.6)	7.3 (6.6)
	Stained		25.0	100.1 (4.0)	1.4 (1.1)
	Unstained	Vacuum- pressure 10 min (new PF resin)	12.5	92.5 (12.6)	2.0 (2.1)
	Stained		38.0	95.9 (5.4)	0.1 (2.3)
Solid MPB block	Unstained	None	0.0	126.2 (23.7)	58.8 (5.1)
	Stained		0.0	150.5 (25.8)	59.7 (2.7)
Mill made MPB plywood	Mixed	Apply a PF glue mix	2.5	147.8 (21.5)	47.6 (9.2)
Solid ponderosa pine sapwood	Unstained	None	0.0	127.5 (53.9)	53.9 (15.6)

Note: * The averages were base on six samples, and data in brackets are standard deviations.

Mass losses of 53.9% on the Ponderosa pine and around 59.0% on stained and unstained lodgepole pine controls given by *C. puteana* demonstrated that this fungus was sufficiently aggressive to discriminate among treatments (Table 10). Mill-made MPB plywood and unnstained MPB plywood with 5 min of dipping/soaking in the low MW PF resin showed similar substantial mass losses of 47.6% and 45.3%, respectively. The stained MPB plywood with 5 min of dipping/soaking in the low MW PF resin showed reduced mass loss of 17.9%. When the new PF resin was used, the unstained MPB LVL with 5 min of dipping showed negligible reduction in mass loss (50.9%) but there was some reduction (to 38.5%) with the stained MPB LVL with 5 min of dipping. Complete control of decay (below 3% mass loss) was exhibited by the stained and unstained MPB LVL with 6 h of dipping and 10 min of vacuum-pressure treatments. With 5 min of vacuum-pressure treatment, the stained MPB LVL showed less than 3.0% mass loss but the unstained counterpart had 7.3% mass loss. Note that in treatments where mass losses were low, equilibrium MCs of the test blocks ranged from 75.6% to 106.2% indicating that the treatment is extremely hygroscopic and the high MC may have excluded oxygen to help inhibit decay.

Weight loss, in tests of solid sapwood, typically ranges from 20% to 65% over a 12-week test period, depending on the fungus and wood species. In contrast, similar tests with wood plastic composite (WPC) blocks produced wood-weight losses of 5% to 10% (Silva et al. 2007). Figure 39 shows how weight losses relate to PF resin-solids uptake for EWPs made from the MPB veneers when exposed to the brown fungus (*Coniophora puteana)* for 12 weeks in a soil block decay test. The results indicated that the weight loss was reduced with increasing resin-solids uptake. Once the PF-resin solids reached a threshold level of about 15%, the weight loss of resulting EWPs was below 3%, a level to achieve complete control of decay. Weight loss at this threshold level was also less than that of WPC, which is very encouraging. The

final judgement will be made when the test results of the ACQ treated reference material and white-rot fungus (*Irpex lacteus*) are available.

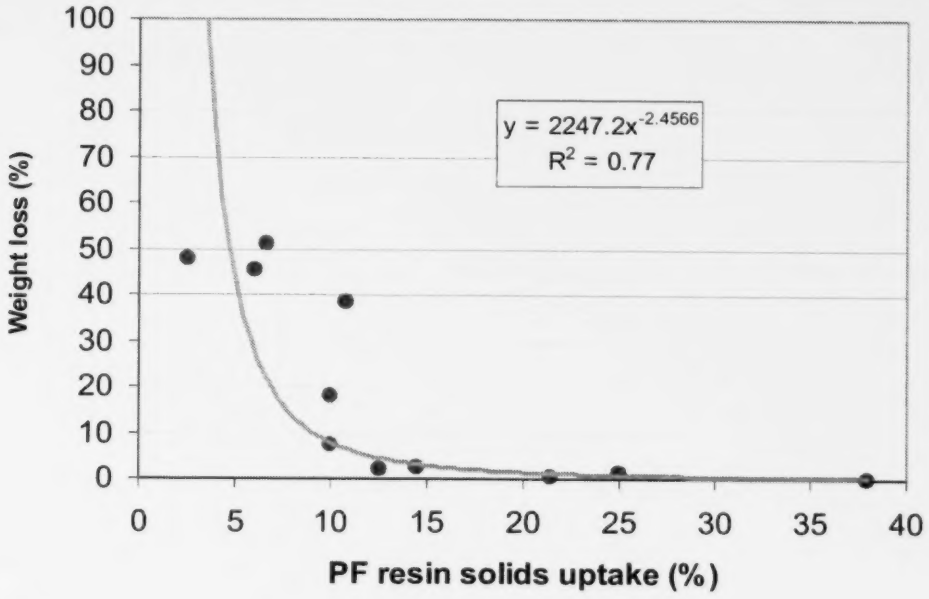


Figure 39. The relationship between weight losses and resin-solids uptake after 12 weeks' exposure to *Coniophora puteana* in a soil block decay test.

3.5 Economic Impact

As demonstrated, for mixed MPB veneers (stained and unstained inclusive), dipping 5 min in the new PF resin increased resin solids consumption by about 6%. Dipped veneer sheets can be dried to a relatively high MC (10%–15%), and further glue applications can be eliminated for manufacturing LVL and specialty plywood products. The resulting products have improved hardness, stiffness, strength, and dimensional stability. More importantly, the stain in MPB wood can be completely masked or modified, eliminating cosmetic concerns. As a result, value-added plywood and LVL can be manufactured for various industrial and structural applications.

Currently, the price of PF resin is about $ 0.94/kg on a liquid (55% solids content) basis, which is about $1.71/kg for the solids. Assuming the average density of dried MPB veneers is 460 kg/m^3, this additional 6% resin-solids uptake will consume about 27.6 kg/m^3 resin solids, which is equivalent to an additional resin cost of $47.2 /m^3. Additional labor costs for resin treatments could increase the total cost to $100/m^3. With 5-min of resin impregnation, it is possible to utilize low-grade MPB veneers to manufacture high-grade LVL. Therefore, at the current resin price, the utilization of the new resin impregnation technology will achieve significant economic gains for LVL producers. The price gap between the two LVL grades is estimated at $200-300/m^3, and the overall material recovery from logs to LVL products is approximately 50%. As a result, for one plywood/LVL mill with MPB wood procured exceeding 10% of the total log supply (typical log annual consumption is 400,000 m^3), the net benefit will be greater than $2,000,000 per year, considering 400,000 m^3 x 10% x 50% x ($200 /m^3 - $100 /m^3) = $2,000,000.

4 Conclusions

The results of this research provide impetus for renewed interest in resin impregnation technologies for manufacturing high-performance and durable veneer-based EWPs, such as LVL and specialty plywood. A PF resin was developed to treat MPB veneers with a simple dipping/soaking method, and it successfully masks the blue stain in MPB wood. Further glue applications after drying can be eliminated, making the manufacture of EWPs simpler and more cost-effective. The new resin-impregnation technology is equally applicable to other common Canadian species, such as spruce and aspen.

Resin-solids uptake was significantly higher in stained than in unstained MPB veneers, and much lower in green than in dried MPB veneers. With 5 min dipping/soaking in the new resin and oven-drying for 1 h, the stain colour in the MPB veneers can be sufficiently masked to manufacture *stain-free* MPB plywood cost-effectively. Products had higher bending and shear strength, greater hardness, and better appearance and dimensional stability, making them suitable for value-added structural and industrial applications.

Veneer-MOE enhancement correlated well with resin-solids uptake for MPB LVL. At the same treatment time, stained MPB veneers had higher MOE enhancement than unstained MPB counterparts. Dipping in the resin for 5 min seemed to be cost-effective, yielding resin-solids uptake of 6.6% in unstained and 10.3% in unstained MOB veneer, in turn enhancing veneer MOE by 5% and 8%, respectively. The resulting LVL products were harder, higher in shear strength and bending MOE and MOR, and had better dimensional stability, meeting 2.2E and 1.9E LVL market requirements with no cosmetic concerns. This rapid-resin treatment for the MPB veneers can help raise the LVL by one grade to recover higher value. Increasing resin-solids uptake further provided less significant enhancement of veneer MOE. Thus, an optimum level of the resin-solids uptake should be established to balance the manufacturing cost and product performance for specific end uses.

Soil-block tests of various MPB plywood and LVL exposed to a brown-rot fungus (*Coniophora puteana)* demonstrated that the weight loss was significantly reduced with increasing resin-solids uptake. Once the resin-solids uptake achieved a threshold level, around 15%, the products showed a weight loss of < 3%, a complete control of brown-rot decay, making them suitable for exterior applications such as above-ground or ground contact without further preservative treatment. However, a general conclusion on durability cannot be made until the decay-test results with a white-rot fungus are available. Field tests may also be required to further assess the durability of the PF resin treated plywood and LVL.

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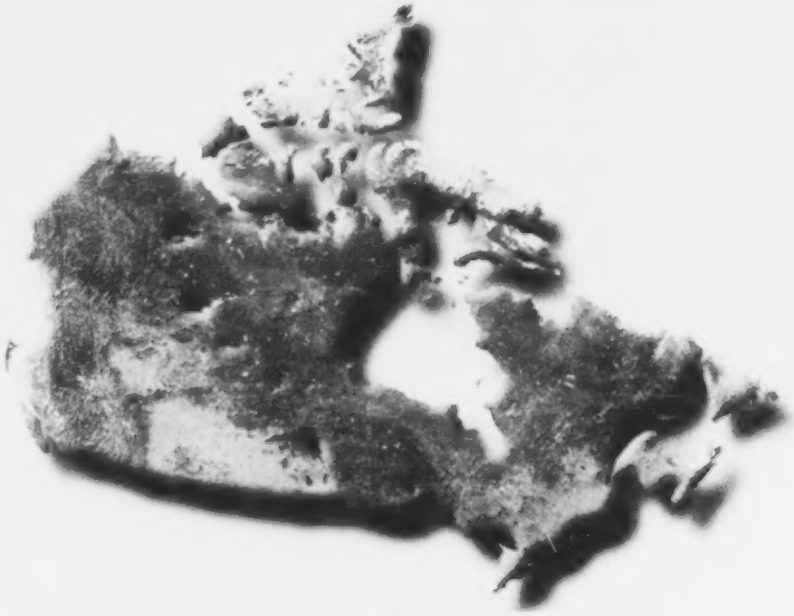

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